

General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

9950-690

(NASA-CR-169207) INFRARED AIRBORNE
SPECTRORADIOMETER SURVEY RESULTS IN THE
WESTERN NEVADA AREA Final Report (Columbia
Univ.) 64 p HC A04/MF A01 CSCI 08B

N82-29678

Unclas
G3/43 30275

INFRARED AIRBORNE SPECTRORADIOMETER
SURVEY RESULTS IN THE WESTERN NEVADA AREA

BY

WILLIAM COLLINS

SHENG-HUEI CHANG

JOHN T. KUO

Aldridge Laboratory of Applied Geophysics

Columbia University

New York, New York 10027



Final Report to NASA, Contract JPL 955832

This Work Was Performed For The Jet Propulsion
Laboratory, California Institute Of Technology,
Sponsored By The National Aeronautics And Space
Administration Under Contract NAS7-100

MAY 1982

CONTENTS

ABSTRACT.....	Page i
I. INTRODUCTION.....	1
Background.....	2
Instrumentation.....	4
Data Analysis Techniques.....	5
II. SURVEY AREAS.....	8
III. SURVEY RESULTS.....	12
Mud Lake Traverse.....	12
Goldfield Survey.....	15
Cuprite Survey.....	29
Silver Peak Survey.....	32
Candelaria.....	37
Gillis Range.....	47
Jim Canyon and Sweet Water Sites.....	53
IV. CONCLUSIONS AND RECOMMENDATIONS.....	59
REFERENCES.....	61

ABSTRACT

The newly developed Mark II airborne spectroradiometer system was flown over several geologic test sites in western Nevada. The infrared mineral absorption bands were observed and recorded for the first time using an airborne system with high spectral resolution in the 2.0 to 2.5 micron region. The data show that the hydrothermal alteration zone minerals, carbonates, and other minerals are clearly visible in the airborne survey mode. The finer spectral features that distinguish the various minerals with infrared bands are also clearly visible in the airborne survey data. Using specialized computer pattern recognition methods, it is possible to identify mineralogy and map alteration zones and lithologies by airborne spectroradiometer survey techniques.

I INTRODUCTION

The Columbia University, Mark II Airborne Spectroradiometer System was flown over several exposed terrain test sites in southwestern Nevada in October 1980. The new instrument system, in addition to the 512 channels of silicon detectors, has 64 channels of PbS detectors sensitive in the 1.1 micron to 2.5 micron region. This experiment marks the first time that a spectroradiometer system of relatively high spectral resolution in the infrared has been flown over natural geologic targets. The spectroradiometer systems are designed for spectral resolution similar to or greater than the natural bandwidths of mineral and biogeochemical materials. This type of system has the best available sensitivity to the geologically important spectral features in natural terrain. The high spectral and radiometric sensitivity has been proven critical in biogeochemical exploration applications (Collins et al, 1980a, 1980b), and has been shown in the present research to be critical for infrared identification and mapping of minerals and lithologies.

The present knowledge of infrared properties of minerals and rocks has come mainly from the laboratory studies of Graham Hunt (e.g. Hunt, 1979). The principle objective of the present airborne surveys was to determine if the spectral properties of minerals and rocks as observed by Graham Hunt could be observed with similar clarity under natural field conditions with airborne survey instruments. The results of this first series of airborne surveys have been very successful in showing that the important mineral

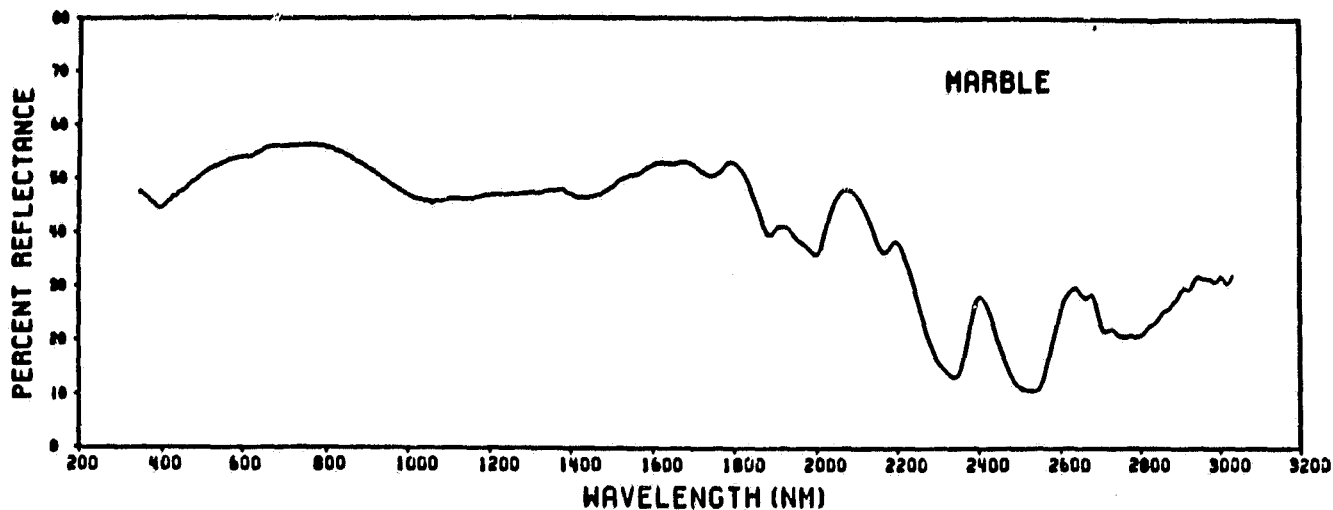
features can definitely be distinguished very clearly and with a high degree of spectral and radiometric sensitivity using airborne spectroradiometer techniques. Spectroradiometer instruments are a new geologic exploration tool that can be presently incorporated into geologic mapping and exploration programs, and they can also be a very useful tool in research and applications programs related to NASA's orbiting spatial scanner systems.

Background

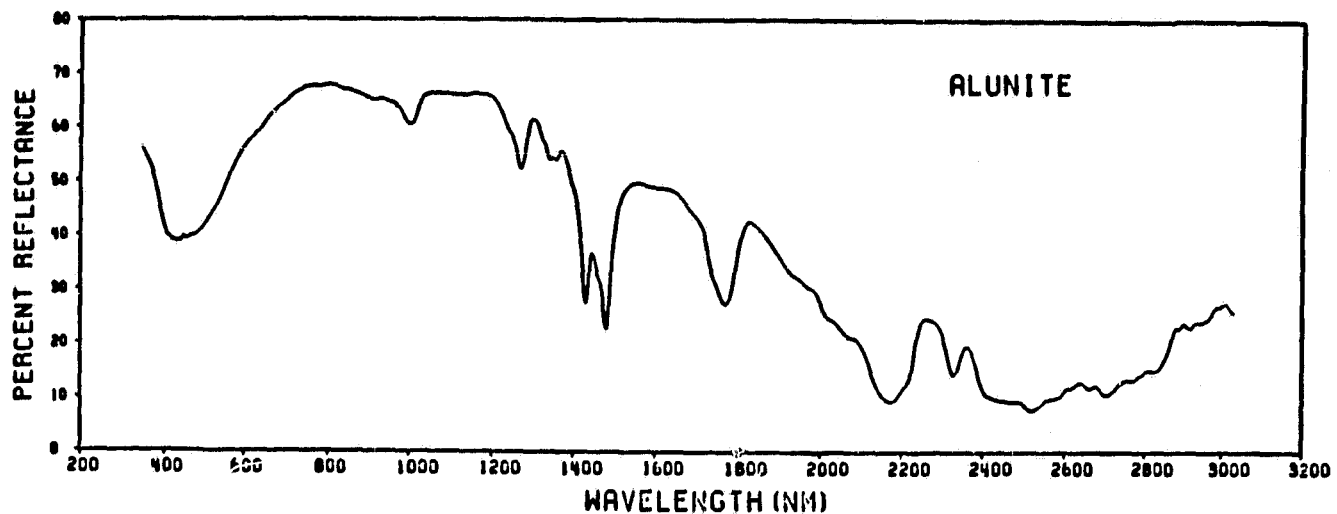
The importance of the infrared spectral properties of clay minerals associated with hydrothermal alteration, and the infrared features of other minerals such as the carbonates, were recognized by Graham Hunt and documented in several publications (eg. Hunt, 1979). Some recent examples of the visible and infrared spectral curves of minerals in whole rock hand samples are shown in Figure 1. These measurements are made in the laboratory using a regulated tungsten lamp. Characteristic absorption features appear in several parts of the spectrum. The features in the 1.4 to 1.6 micron and 1.8 to 2.0 micron regions, however, are obscured by atmospheric water absorption bands when measurements are made in the field using the solar source. The most useful part of the spectrum under field conditions is the 2.0 to 2.5 micron "atmospheric window", where the clays and many other minerals have distinctive absorption features.

When viewed by spectroradiometer instruments with wavelength

PORTABLE SPECTRORADIOMETER MEASUREMENT



PORTABLE SPECTRORADIOMETER MEASUREMENT



PORTABLE SPECTRORADIOMETER MEASUREMENT

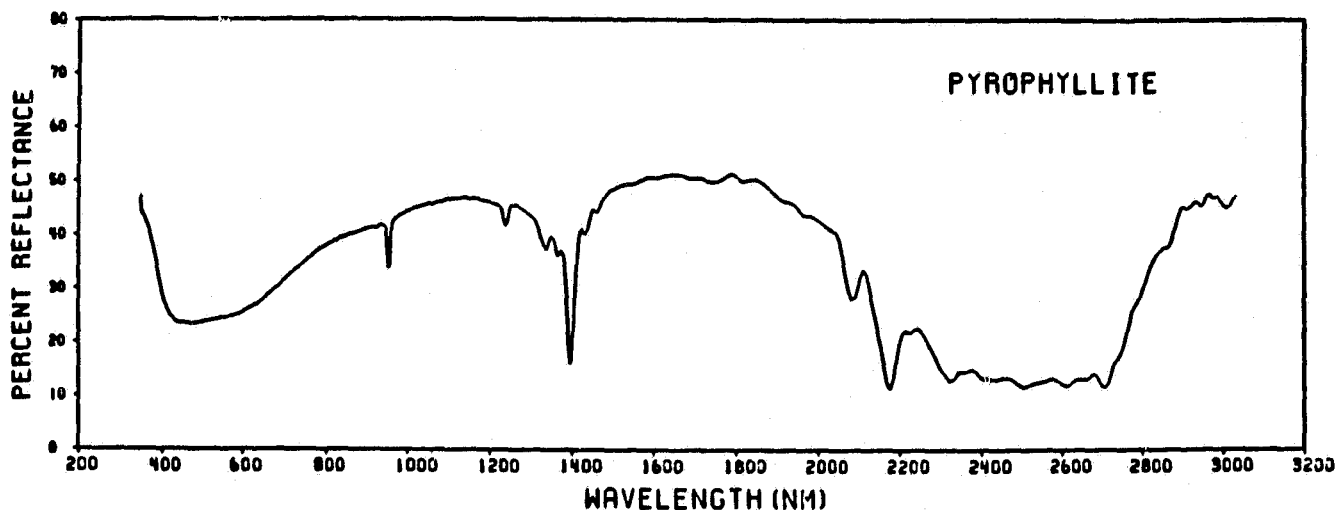


Figure 1. Laboratory measurements of whole rock field samples containing the above minerals.

resolutions equal to the natural bandwidths of the various mineral features the various minerals with 2.0 to 2.5 micron absorption features can be specifically identified. The basic premise in spectroradiometer applications is (1) that the instruments must have the necessary spectral and radiometric resolution to detect the specific features of minerals or biogeochemical materials, and (2) that the data analysis techniques are adequate to take full advantage of the range of instrument capabilities.

Instrumentation

The Mark II instrument system was designed and developed at Columbia University with funding from the National Science Foundation, Division of Engineering. The system design is similar to that of the Mark I system described by Chiu and Collins (1978). In contrast to the Mark I system, the Mark II system uses all solid state detectors. The spectral range covered is from 350 to 2500nm, using a silicon-diode array for the 350 to 1000nm segment and a lead-sulfide array for the longer wavelength region.

The high spectral-resolution data in the near-infrared presented in this report are obtained by means of a 64-element linear array of lead-sulfide detectors. The array is positioned at the exit focal plane of a 275mm focal-length spectrograph. All channels receive the spectrally dispersed 64 bands of energy in parallel as the field-of-view on the ground is swept along the aircraft ground track. The instrument integrates the energy in each band simultaneously over contiguous 20-m-square areas along the survey

flight path at 600 miles above terrain. The 64 channel data for each 20-m-square field-of-view are recorded on computer-compatible tape for later processing. The data are calibrated band by band for radiance received at the front aperture. Location of the spectra on the ground is achieved by mosaicing 35mm color photographs that are acquired simultaneously with the spectral data.

The most critical aspect of this type of spectroradiometer system is that each of the measurements in the 64 spectral bands taken from a moving platform are precisely registered on the same ground target. The parallel optical input also results in a high signal-to-noise ratio and very good radiometric resolution of spectral features at high data-acquisition rates. A high signal-to-noise performance in narrow spectral bands is especially important in this airborne application because of the subtle expression of many of the spectral features.

Data Analysis Techniques

The data were analyzed by several techniques. A waveform analysis technique similar to that used on spectral data from vegetated terrain (Collins, et al 1981a) was found to give the best results. A discrete-narrow-band-ratio approach correlates in some areas with the waveform results. In other areas, however, the discrete band ratios do not give good results. The bands chosen for the discrete band analysis are shown in Figure 2. The bands are 8nm wide

ORIGINAL PAGE IS
OF POOR QUALITY

POSITIONS OF 8 NM WIDE BANDS FOR DISCRETE BAND STUDIES

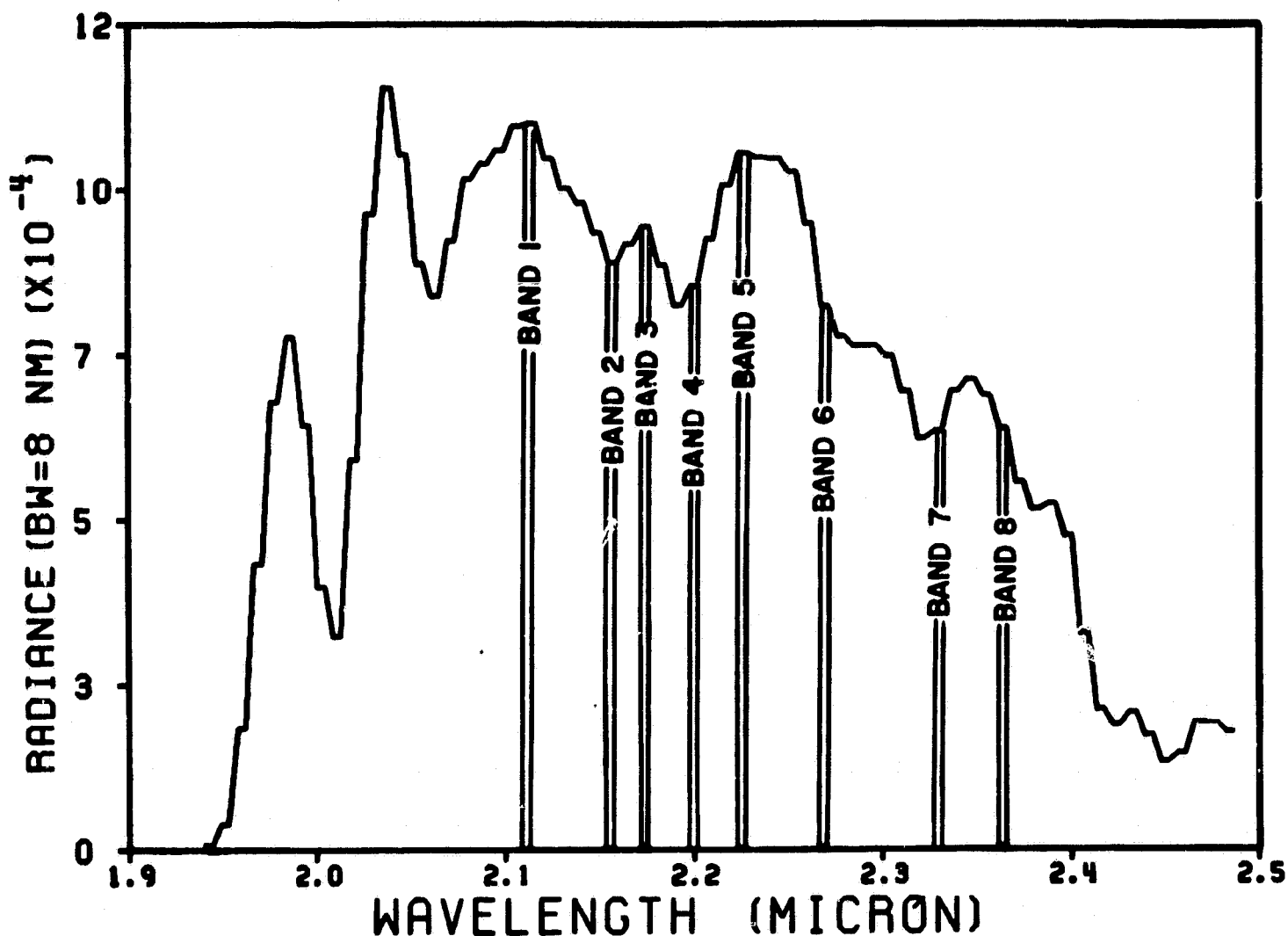


Figure 2. Infrared aircraft spectrum from hydrothermally altered zone. The indicated narrow bands are selected for sensitivity to mineral band features when used in a band ratio analysis.

and are chosen for sensitivity to the mineral features. The analysis also includes visual inspection of individual infrared spectral curves.

The basic problem in analysis of the new infrared mineral data is one of pattern recognition in a spectrum that can vary widely in many spectral regions due to all of the possible mineral bands and combinations of mineral bands. The more familiar multi-band approach to IR mineral data can lead to confusion because of all the possible spectral variations that are still not well enough known. This leads to the problem of where to select bands and how to interpret the results.

The approach, of a waveform analysis based on a best fit of Chebyshev polynomials, can be referred to as a "general" pattern recognition approach that simply searches for the various spectral differences among the data. The "specific" pattern recognition approach would be to replace the Chebyshev polynomials with a family of known mineral spectral curves. This is essentially what is attempted in visual inspection of the data. The specific pattern recognition technique will allow separation and identification of minerals or groups of minerals in each measurement. This technique will be optimum, but it will take further development effort that will depend heavily on ground and laboratory measurements correlated with the aircraft data. The present best technique is a combination of the more general Chebyshev waveform analysis, and various band analyses, coupled with visual inspection and correlation with laboratory and ground spectral measurements.

II SURVEY AREAS

The aircraft surveys covered eleven sites in the Walker Lake and Goldfield areas in southwestern Nevada. The survey areas are located in the LANDSAT photo mosaic in Figure 3. The southern survey areas are shown in larger scale in the LANDSAT frame of Figure 4. A survey line was flown over Mud Lake to obtain reference data for background conditions. Two traverses were flown over the Goldfield district of well mapped hydrothermal alteration. Several traverses were also flown over the altered area in Cuprite.

The traverses flown in the Silver Peak area to the west in Figure 4 covered areas of different, unaltered, lithologies. The Silver Peak traverse crosses a volcanic tuff unit. The Paymaster traverse is along the Paymaster Ridge phyllite. The Lone Mountain traverse crosses an igneous intrusive in contact with a marble unit.

Five areas were flown in the Walker Lake area shown in the LANDSAT scene of Figure 5. The traverses in Candelaria and Garfield Flat covered mostly metasediments. The two traverses in the Gillis Range crossed zones of different hydrothermal alteration. The traverses across Sweet Water and Jim Canyon covered altered zones that are mostly obscured by vegetation and snow.



Figure 3. LANDSAT photo mosaic of the state of Nevada showing the locations of survey sites.

ORIGINAL PAGE IS
OF POOR QUALITY



Figure 4. LANDSAT frame of the Goldfield, Nevada, region. The airborne survey traverses are shown in more detail in white.

ORIGINAL PAGE IS
OF POOR QUALITY

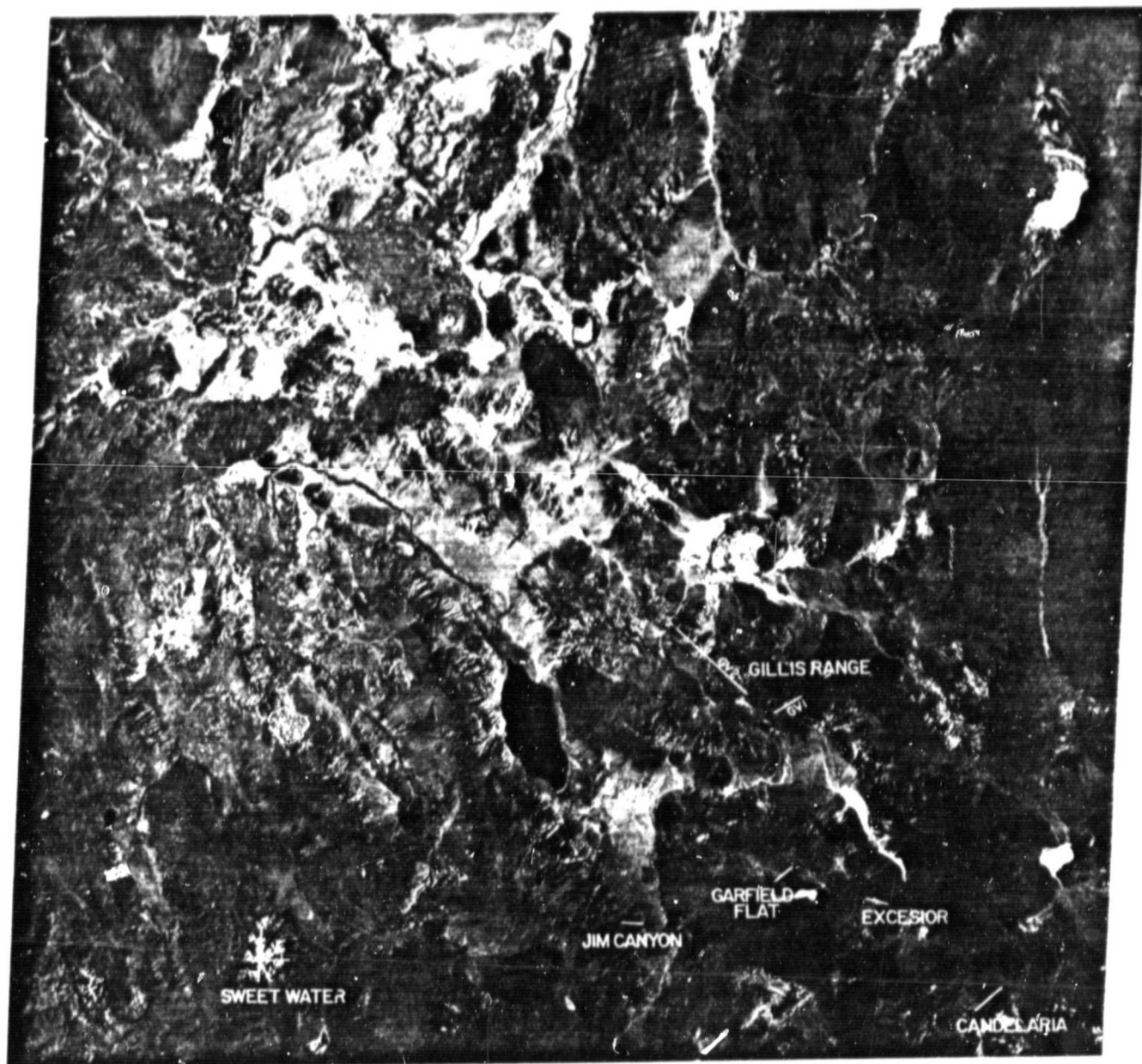


Figure 5. LANDSAT frame of the Walker Lake, Nevada, region. The airborne survey lines flown in this region are shown in white.

III SURVEY RESULTS

Mud Lake Traverse

A single traverse was flown from north to south across the Mud Lake playa to obtain spectral measurements of a "white reflector". Mineral analysis of the Mud Lake sediments by the U.S. Geological Survey (Larry Rowan, personal communication) show mostly silicates and salts with at most 2% kaolinite and other clay minerals. The aircraft data from the Mud Lake traverse in Figure 6 indicate that Mud Lake is very homogenous with some slight infrared spectral differences due to clay on the edges. The waveform coefficient $1/4$ has very little variation across the center of the playa with slight increases at the edges.

Inspection of the spectral curves, of which examples are shown in Figure 7, indicate very little or no clay absorption bands in the 2.2 micron region in the central part of the playa. The lower left spectrum is from measurement 214 along the traverse. The other spectral curves are measurements 4, 6, and 9 at the beginning of the traverse, which crosses the margin of the playa. These spectra show a weak kaolinite doublet at 2.15 and 2.2 microns. This absorption feature is responsible for the slightly higher coefficient $1/4$ values at the edges of the traverse in Figure 6.

The results of the band ratio techniques are shown in the two lower curves of Figure 6. The ratio of bands $5/4$ (see Figure 2) should be sensitive to the 2.2 micron absorption features. This ratio

ORIGINAL PAGE IS
OF POOR QUALITY

MUD LAKE BACKGROUND REFERENCE

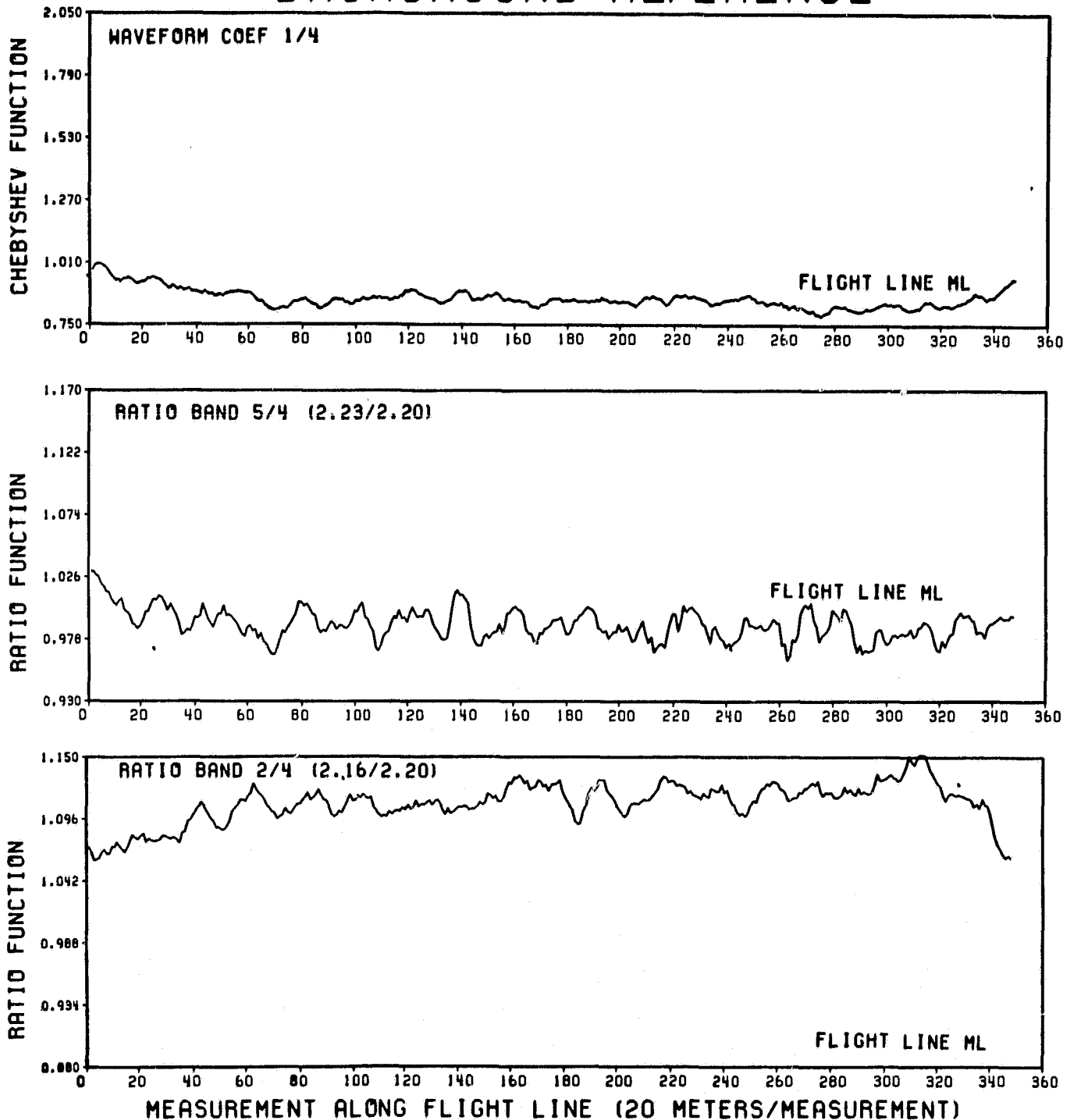
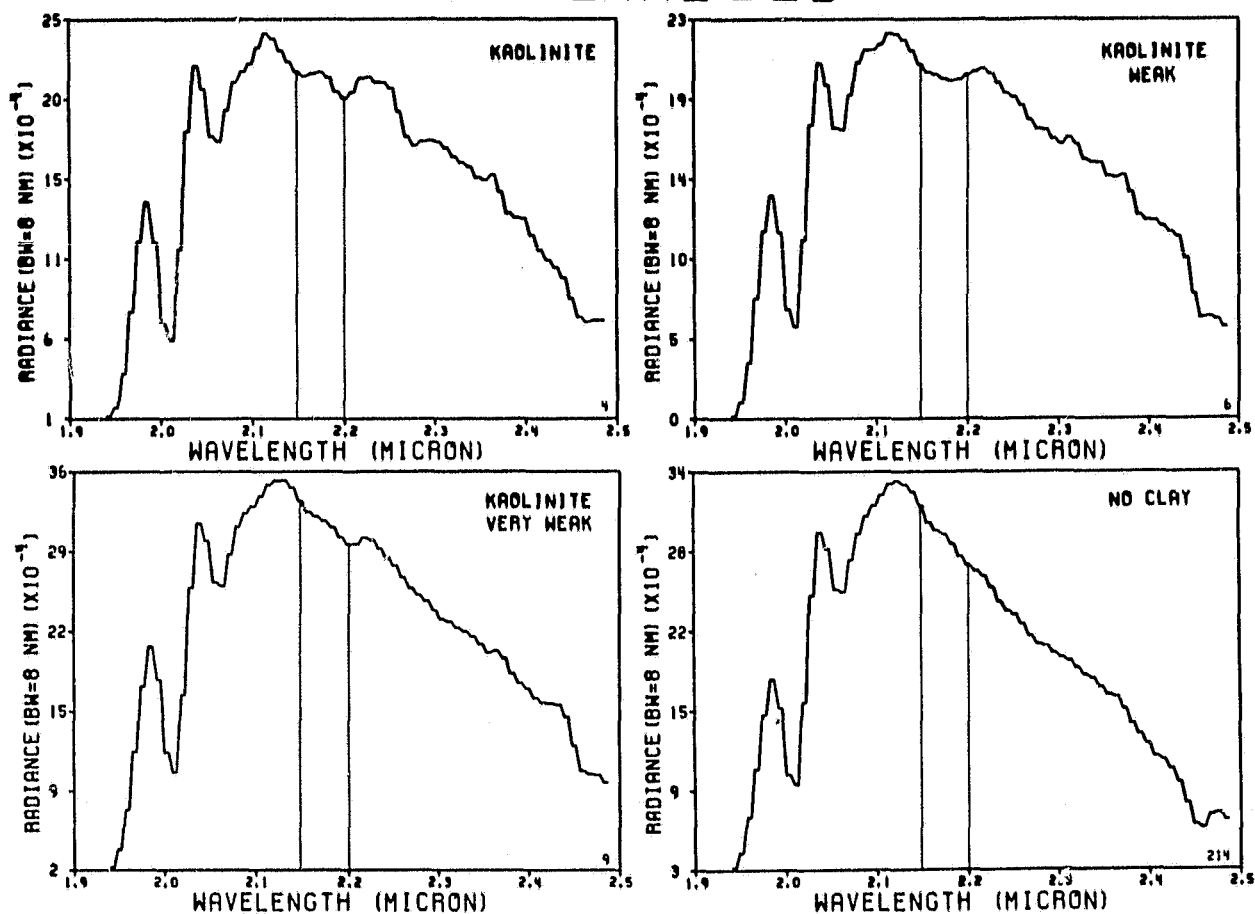


Figure 6. Waveform and band ratio analysis results for the Mud Lake traverse. The waveform function or band ratio is determined for each spectral measurement of 64 bands. There are 350 measurements taken in the traverse across Mud Lake.

ORIGINAL PAGE IS
OF POOR QUALITY

MUD LAKE DRY LAKE BED



FLIGHT LINE ML

Figure 7. Selected individual spectral measurements from the Mud Lake traverse. The numbers in the lower right corner of each spectrum indicate the measurement numbers in the traverse. The spectra are numbers 4, 6, 9, and 214 in the traverse.

is quite a bit noisier than the waveform function, and not sensitive to the variations of kaolinite, or clays, along the Mud Lake traverse. The ratio of bands 2/4 should be sensitive to relative variations in the 2.15 and 2.20 micron features. This ratio appears less noisy and more sensitive to the clay bands in the Mud Lake traverse.

The Mud Lake data is a very useful reference for waveform function and band ratio values to expect in background geologic terrain with no clay alteration minerals or other minerals with infrared absorption features. The Mud Lake data also indicates the sensitivity of the spectroradiometer instruments, which can readily detect the low levels of clay minerals present on the playa surface.

Goldfield Survey

Several traverses were made over the Goldfield district. The traverses were flown along the same lines flown in an earlier survey (Collins, 1978), which are shown by the solid triangle symbols in Figure 8. Two traverses, emphasized in the present report, flight lines 25 and GF2, are indicated by the heavy solid lines. Flight line 25 begins in unaltered volcanics, mostly Goldfield Dacite and Milltown Andesite. The latter half of the traverse crosses into the mapped zone of hydrothermal alteration of the same volcanic rock units. Flight line GF2 begins in the unaltered volcanics and crosses into one of the most highly altered zones east of Blackcap Mountain.

The waveform analysis results for flight line 25 are shown in Figure 9. The Mud Lake reference flight line results for the

ORIGINAL PAGE IS
OF POOR QUALITY

GEOLOGIC MAP OF THE GOLDFIELD MINING DISTRICT, NEVADA
ADAPTED FROM THE USGS OPEN FILE MAP BY R. P. ASHLEY

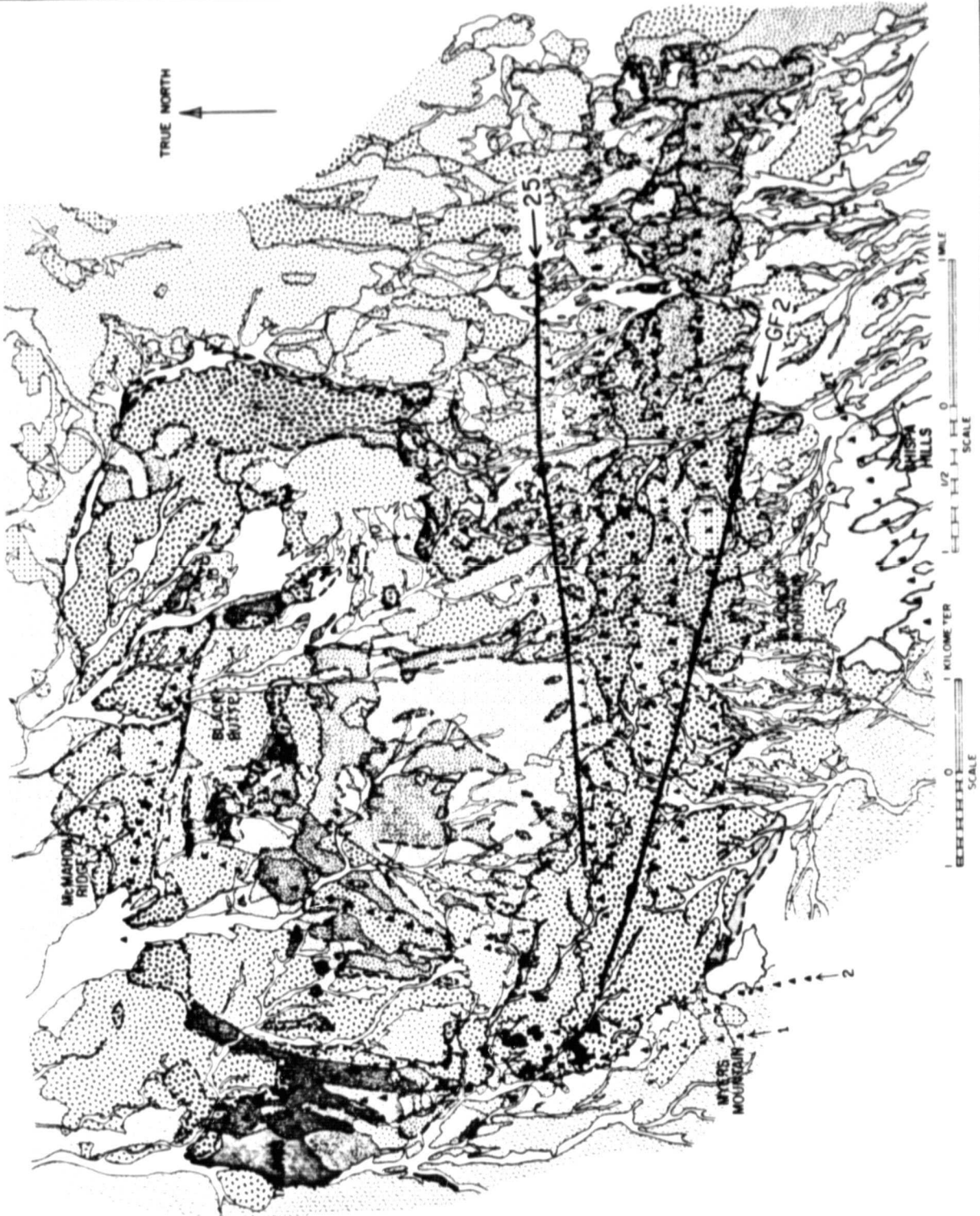


FIGURE 8. SHADED AREA IS THE HYDROTHERMAL ALTERATION ZONE MAPPED BY R.P. ASHLEY, U.S. GEOLOGICAL SURVEY. SOLID LINES ARE THE TWO TRAVERSES FLOWN WITH THE INFRARED SPECTRORADIOMETER.

GOLDFIELD DISTRICT WAVEFORM ANALYSIS

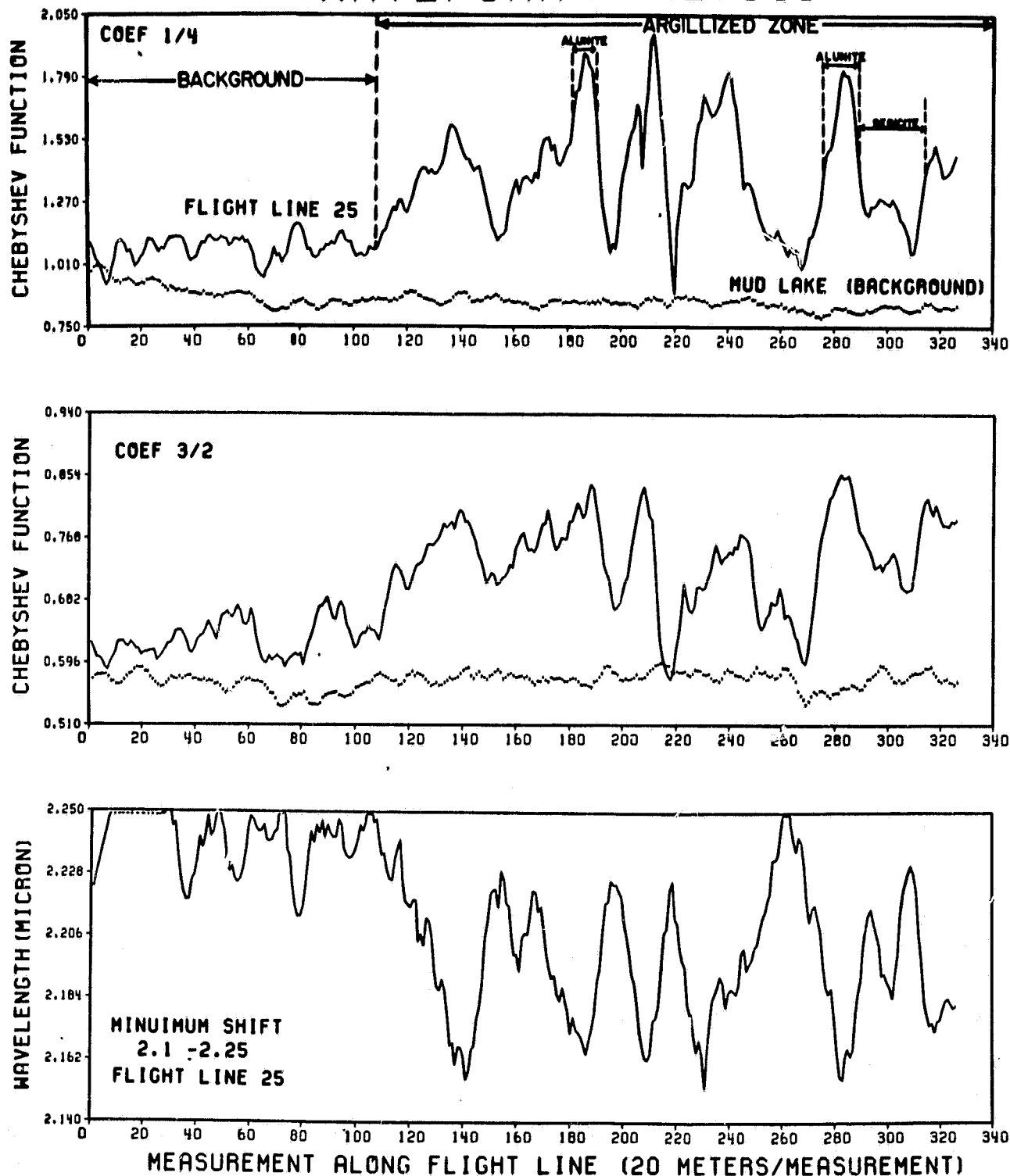


Figure 9. Waveform coefficients 1/4 and 3/2 along traverse 25, Goldfield. Dotted line is the Mud Lake traverse data analyzed by the same coefficients 1/4 and 3/2. Bottom diagram is the location of the local minimum between 2.14 and 2.25 microns for each spectrum in the traverse.

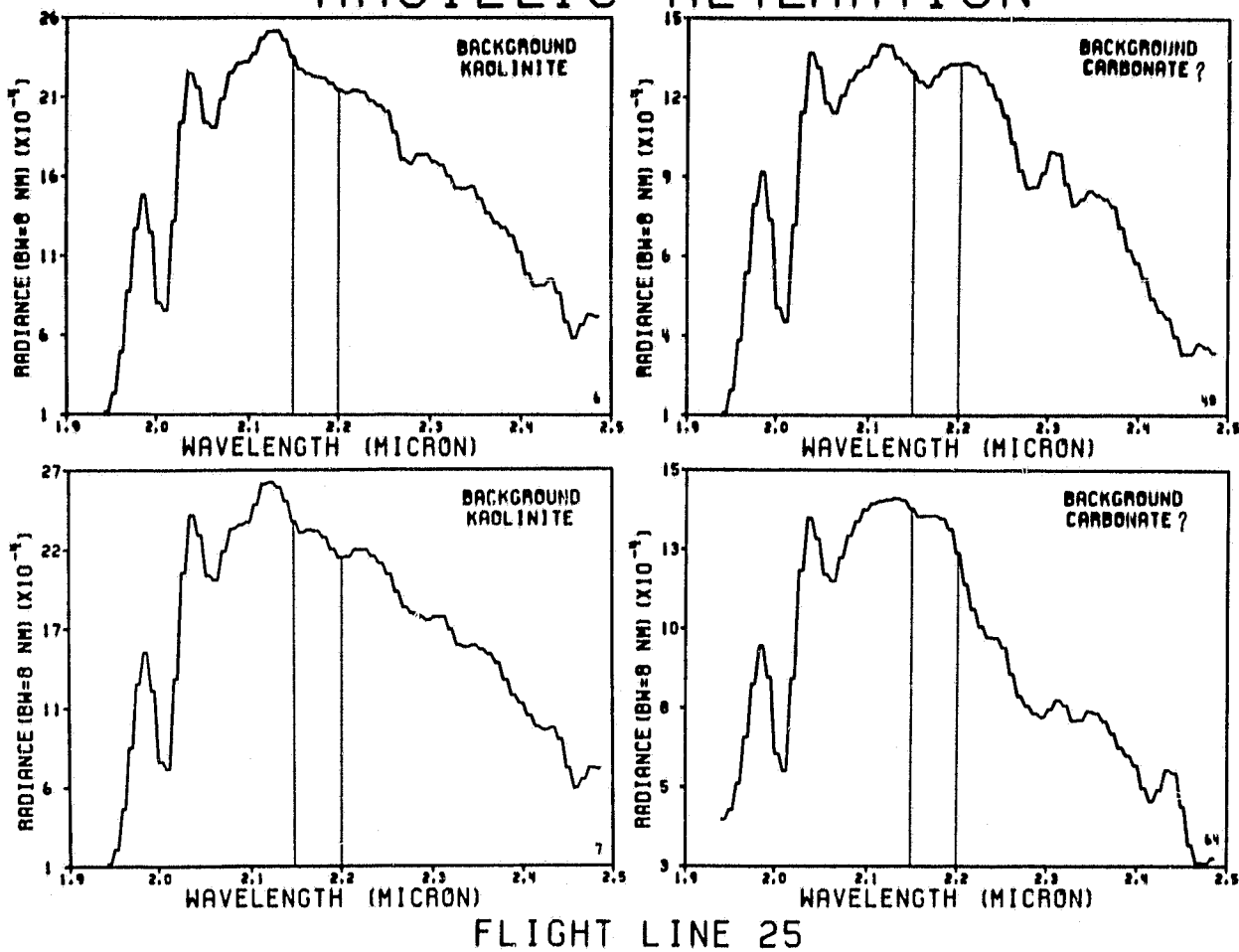
ORIGINAL PAGE IS
OF POOR QUALITY

corresponding waveform or ratio functions are included in each diagram (dotted lines). The waveform coefficient $1/4$ values for measurements 1 through 110 of flight line 25 are a little higher than the $1/4$ values for Mud Lake. This section of the traverse crosses the unaltered volcanics that appear to contain some surface clays. Spectra from the background section, Figure 10, have weak doublet clay absorption bands apparently kaolinite. Other spectra from the background area have a weak 2.16 micron band and a strong broad absorption band near 2.3 microns. These spectral features are similar to the carbonate infrared features seen in Figure 1 and Figure 23.

At measurement 110, flight line 25 crosses into the argillized alteration zone. The coefficient $1/4$ functions rise very noticeably at the alteration zone boundary. The waveform functions also indicate quite variable mineralogy within the altered area. Some typical spectra from the alteration zone crossed by flight line 25 are shown in Figures 11 and 12. The number in the lower right corner of each spectral plot identifies the measurement number in the flight line sequence of Figure 9. The spectra from measurements 183, 188 and 284 show a strong, broad absorption band centered at about 2.175 microns and another band at about 2.33 microns. These features appear very similar to the alunite infrared bands (Figure 1). In general the very high coefficient $1/4$ values correlate with the alunite like spectral features. Frequently the mineral bands in the Goldfield district appear as doublets with a minimum at 2.15 or 2.2

ORIGINAL PAGE IS
OF POOR QUALITY

GOLDFIELD DISTRICT ARGILLIC ALTERATION

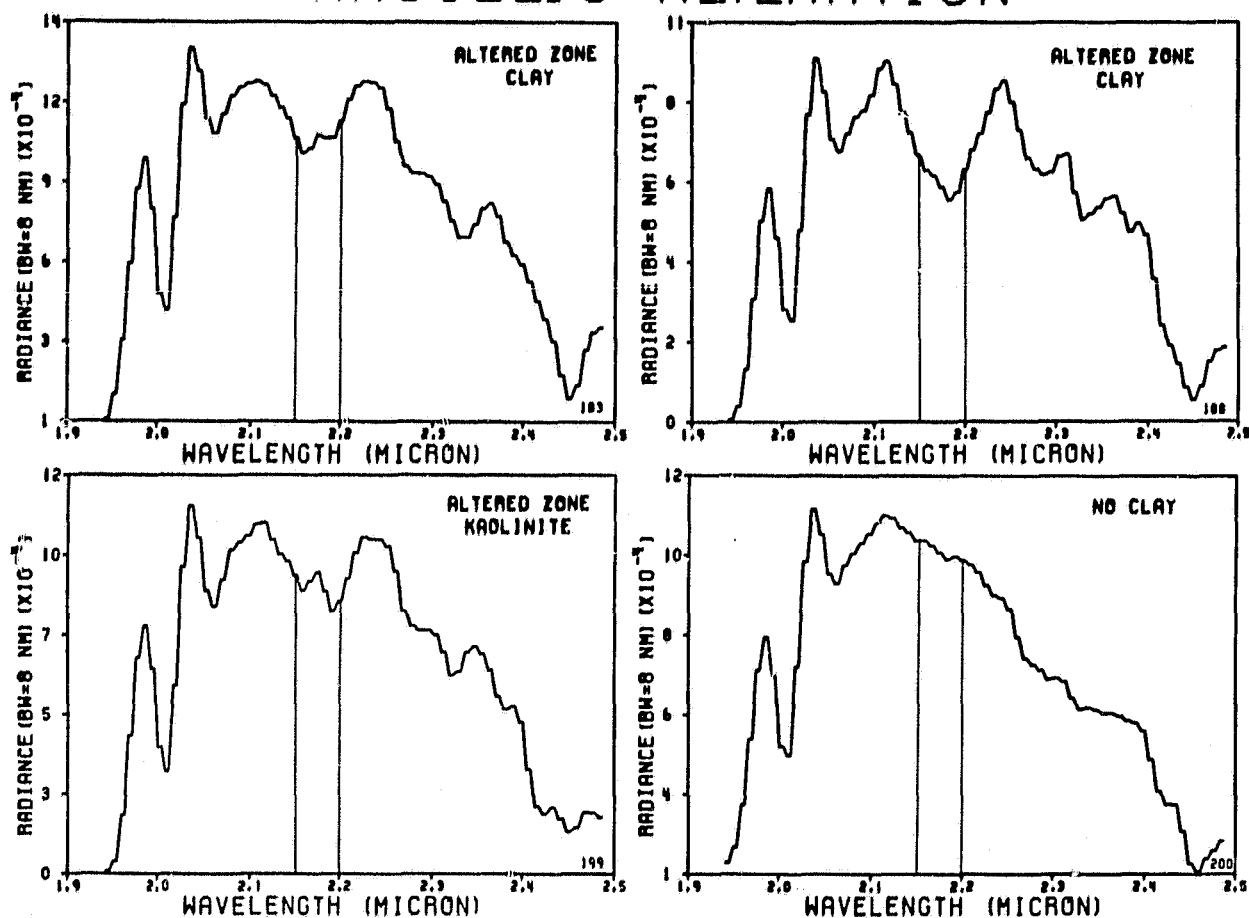


FLIGHT LINE 25

Figure 10. Spectra from measurements 6, 7, 48, and 64 along traverse 25. This area is unaltered.

ORIGINAL PAGE IS
OF POOR QUALITY

GOLDFIELD DISTRICT ARGILLIC ALTERATION

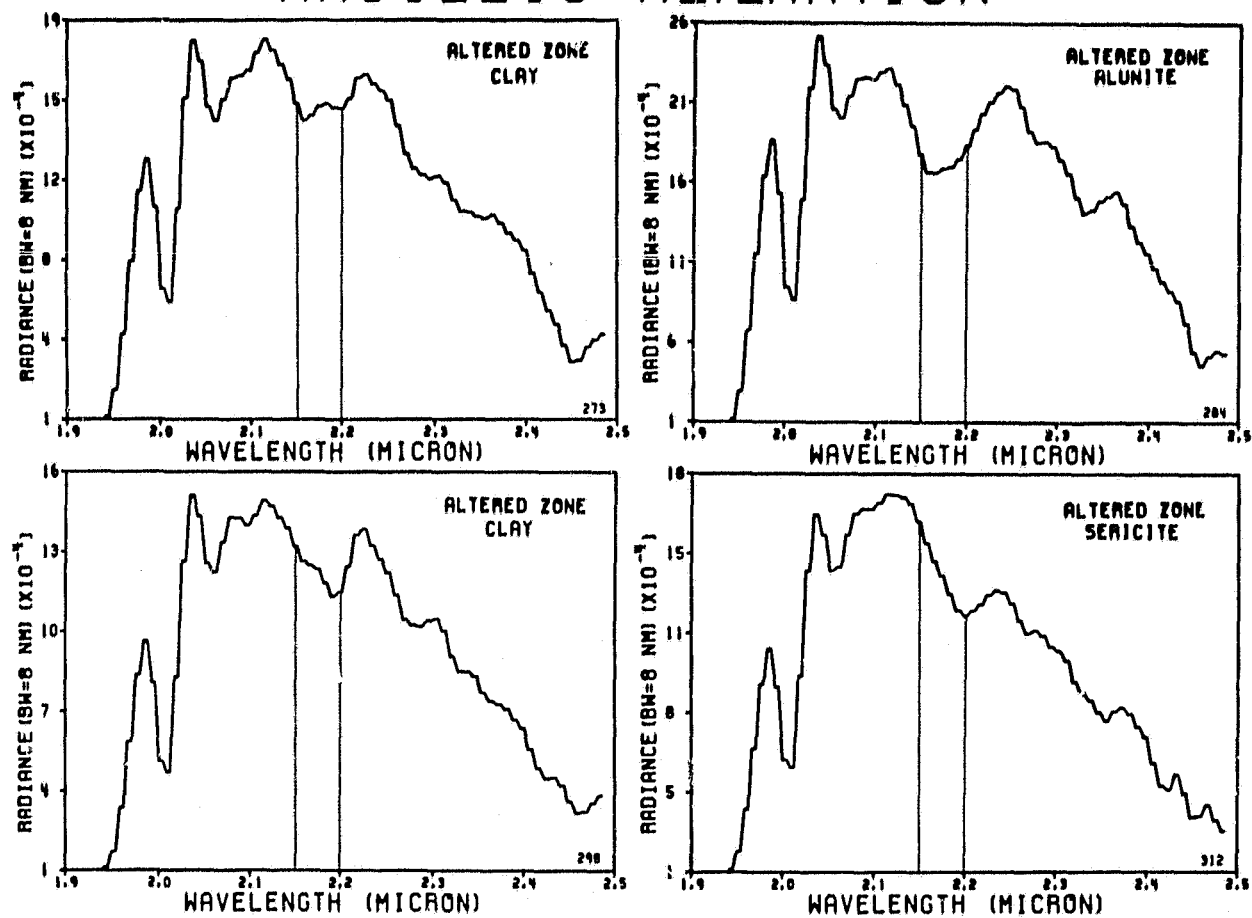


FLIGHT LINE 25

Figure 11. Spectra from measurements 183, 188, 199, and 200 from within the alteration zone along traverse 25.

ORIGINAL PAGE 13
OF POOR QUALITY

GOLDFIELD DISTRICT ARGILLIC ALTERATION



FLIGHT LINE 25

Figure 12. Spectra from measurements 273, 284, 298, and 312 from within the alteration zone along traverse 25.

microns. Some doublets with a 2.2 micron minimum appear to be kaolinite. Others have a 2.15 micron minimum and are tentatively labeled "clay". A zone near measurement 300 has low coefficient $1/4$ values near background. Spectra from this zone, shown in Figure 12, have very strong 2.2 micron bands indicating muscovite, or sericite, (Figure 20) alteration, in this zone.

The generalized waveform analysis is sensitive to a particular spectral feature, depending on how the analysis parameters are chosen. The $1/4$ coefficient function appears very sensitive to the alunite feature and not sensitive to the sharp sericite band at 2.2 microns. The $3/2$ coefficient ratios are shown in the center diagram of Figure 9. This function is more sensitive to the sericite mineralization near measurement 300.

The flight line 25 data were also analyzed by several other techniques for comparison. The lower curve of Figure 9 indicates the position of the clay band minimum in the 2.14 to 2.25 micron region. The minimum is generally at 2.25 microns in the background area indicating no strong clay absorption features. The minimum in the alteration zone shifts toward 2.15 microns in the alunitic zones and to 2.22 microns in zones of stronger kaolinite or sericite mineralization. The results of the minimum shift analysis correlates well with the coefficient $1/4$ analysis in Figure 9. In general the waveform technique using the various combinations of the coefficients of the first five polynomial terms gives the best and most consistent results in all survey areas flown.

Narrow band ratio techniques were tested on the Goldfield data and on data from other areas with inconsistent results. The ratio results for several bands chosen for sensitivity to the clay absorption features are shown in Figure 13. The positions of the bands are shown in Figure 2. Band 4 is in the 2.2 micron absorption feature, and band 5 is on the shoulder. The 5/4 band ratio profile in the center part of Figure 13 is sensitive to the alteration mineralogy, but is also much noisier than the waveform results. The ratios of bands 5/4 in the Goldfield data respond to the sericite bands, as in the data near measurement 300 of flight line 25, and to most other clay features. The ratio variations are about a factor of 2 greater than background over the strong Goldfield alteration zone.

The ratios of bands 1 and 2, shown in the lower part of Figure 13, were chosen for sensitivity to the 2.15 to 2.16 micron absorption features. The results of this ratio are similar to the waveform analysis results in the top diagram of Figure 13, but with more noise in the background area. The band ratios always tend to be the noisier technique resulting in less contrast, or less sensitivity. The waveform techniques consider all points for curve fitting in a given spectral window resulting in noise suppression and greater sensitivity.

The waveform analysis results for flight line GF2 are shown in Figure 14. The waveform analysis along this flight line is sensitive to the general suite of alteration minerals as shown in the co-

GOLDFIELD DISTRICT DISCRETE BAND ANALYSIS

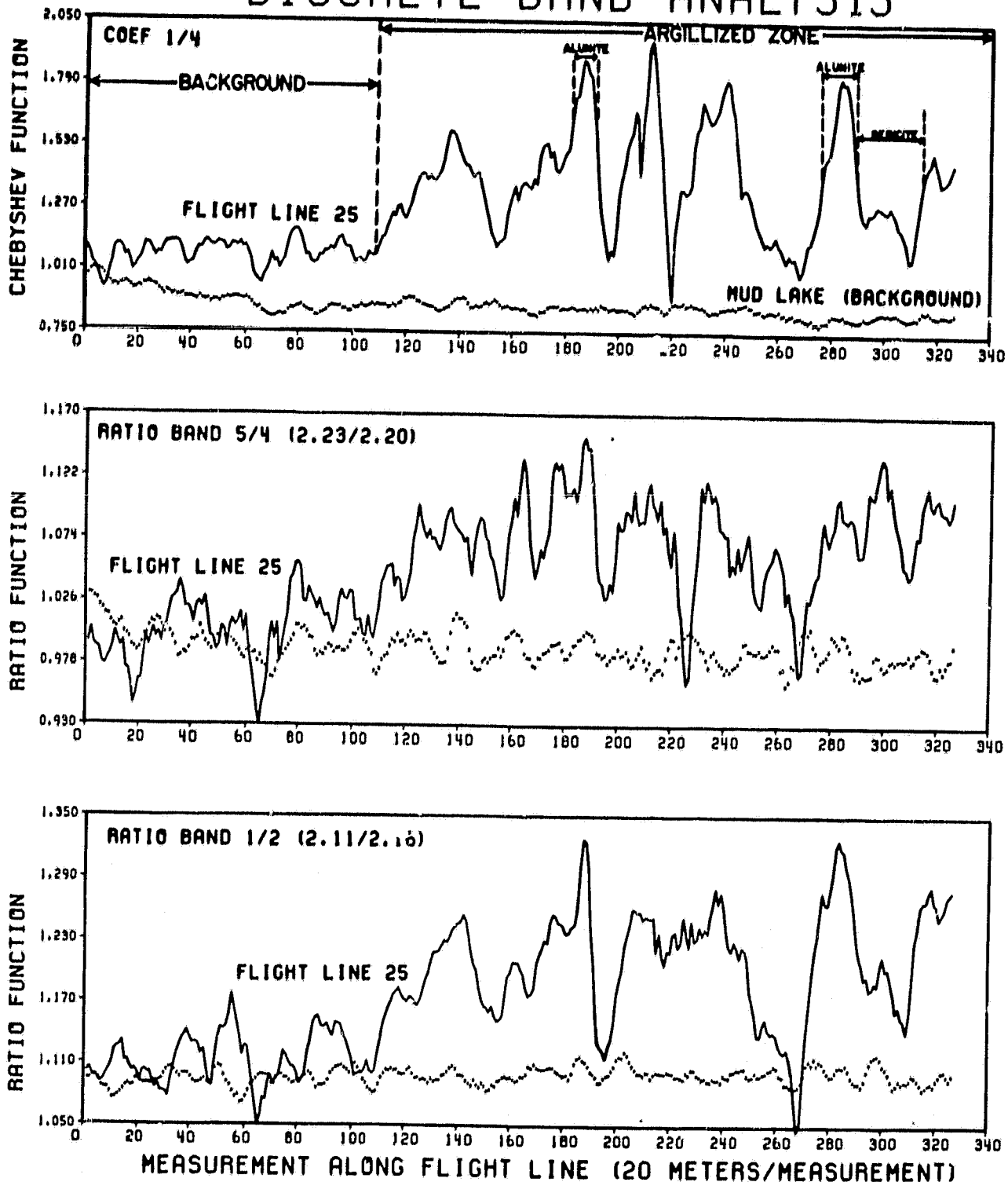


Figure 13. Ratios of bands 5/4 and 1/2 along traverse 25. The waveform coefficient function 1/4 from Figure 9 is included for reference.

GOLDFIELD DISTRICT WAVEFORM ANALYSIS

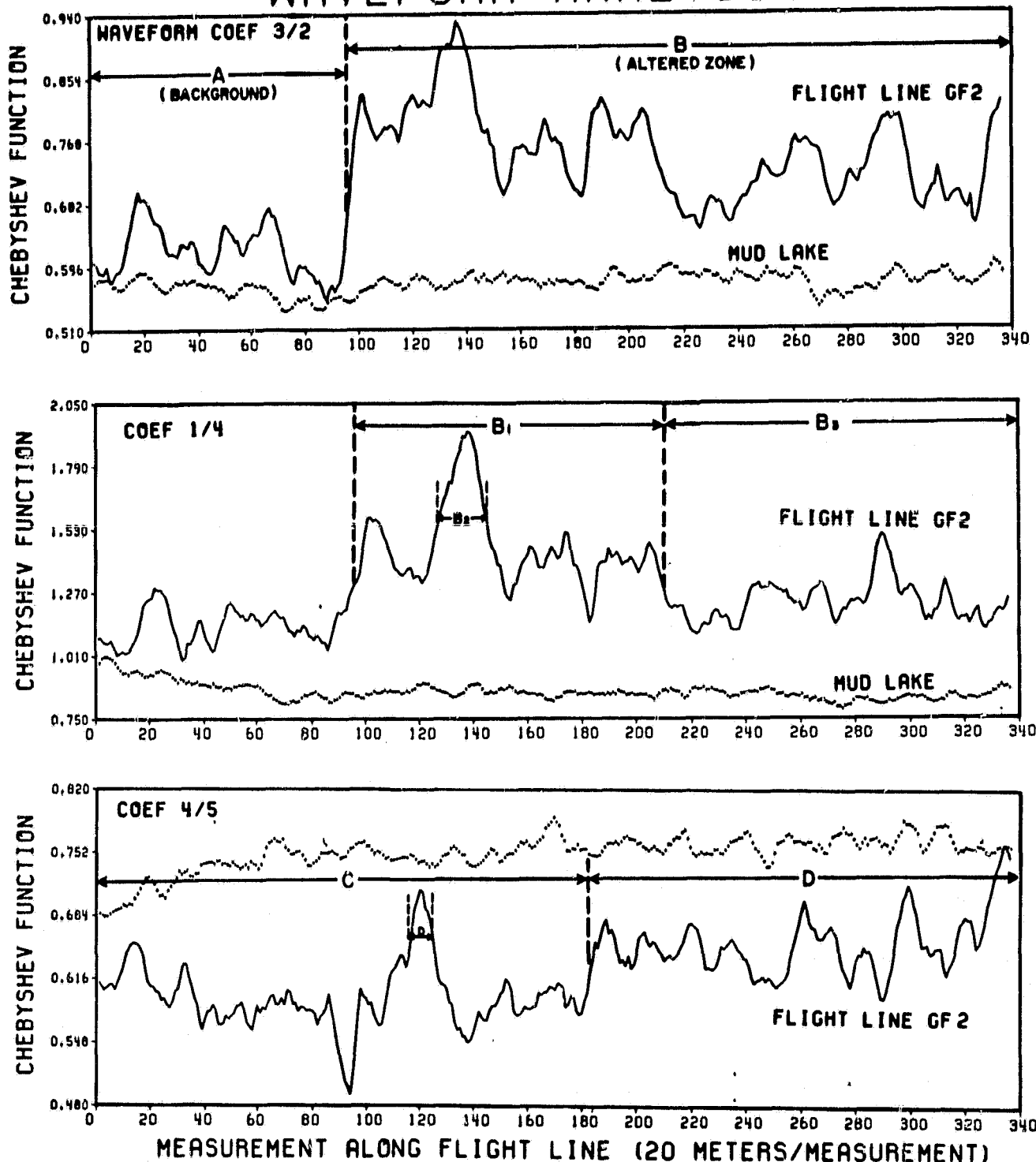


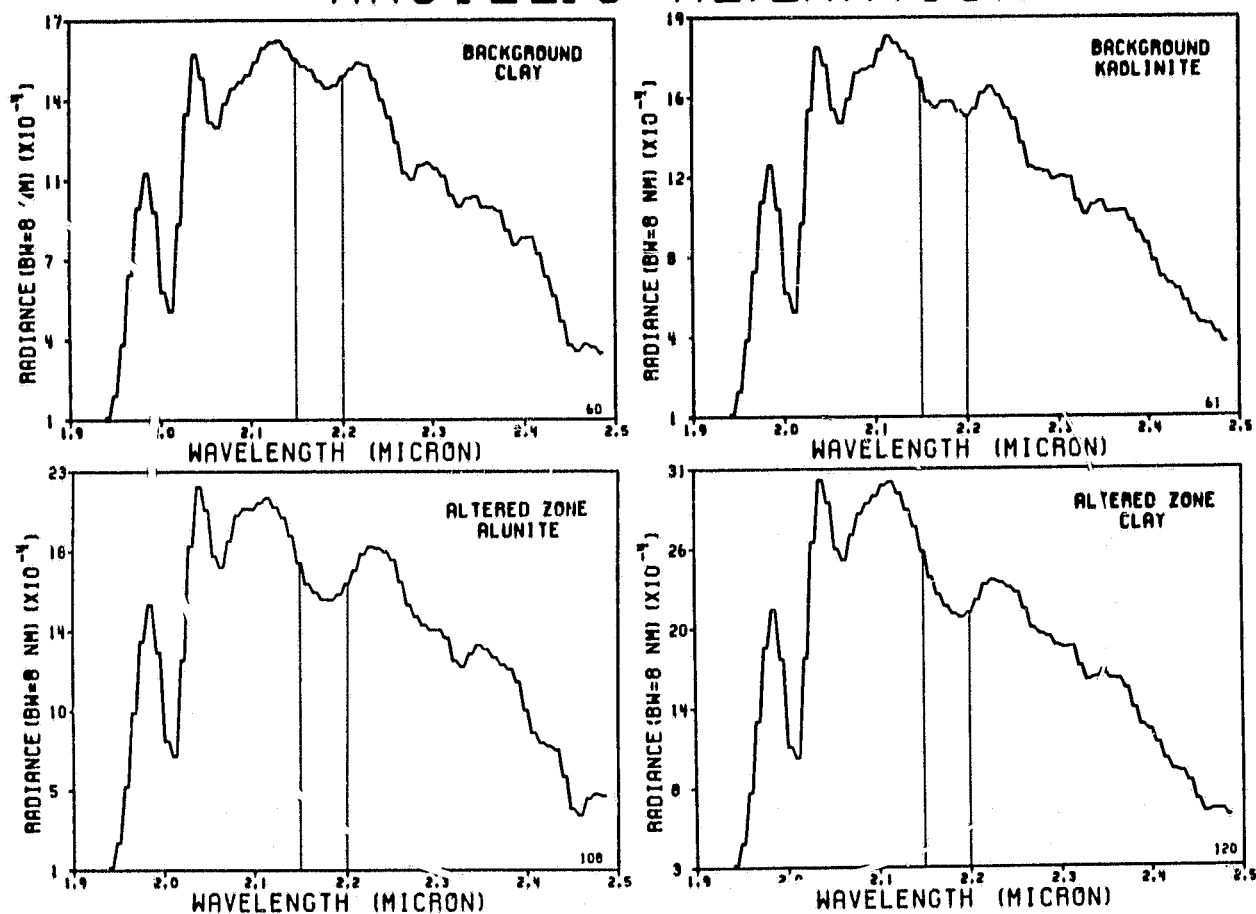
Figure 14. Waveform functions 3/2, 1/4, and 4/5 along flight line GF2, Goldfield. Boundaries between zones A through D are placed at noticeable changes in the trends of the waveform values.

efficient $3/2$ function. There is also a separation of different mineralogies in the alteration zone as shown by coefficient function $1/4$ and $4/5$. The waveform technique appears to distinguish six spectral trends along the flight path, which can be broken down into zones A, B, B_2 , B_3 , C, and D.

Inspection of the spectral curves in Figures 15, and 16 also indicate differing mineralogy. The spectral measurement number in the sequence along the flight path is indicated in the lower left of each plot of Figures 15 and 16. Measurements 60 and 61 in the background zone show moderate clay features, which is in contrast to the much stronger clay features in most spectral curves from within the altered zone. Measurements 108, 120, and 137 show very strong alunite like absorption bands. They are broad and rounded with minima at about 2.17 to 2.18 microns. The absorption feature in measurement 137 is very strong and affects the 2.10 micron shoulder. This measurement is from the distinct zone marked B_2 . The spectral band in measurement 120 shows a shift toward 2.2 microns. The spectrum is from the sharp peak labeled D in the coefficient $4/5$ curve of Figure 14. Spectra 201, 220, and 245 are also from the broader zone labeled D. These spectra all show a 2.2 micron minimum. The waveform analysis and the spectral curves from flight line GF2 show quite conclusively that specific mineral identification and mapping within altered areas can be accomplished with the infrared spectroradiometer.

ORIGINAL PAGE IS
OF POOR QUALITY

GOLDFIELD DISTRICT ARGILLIC ALTERATION

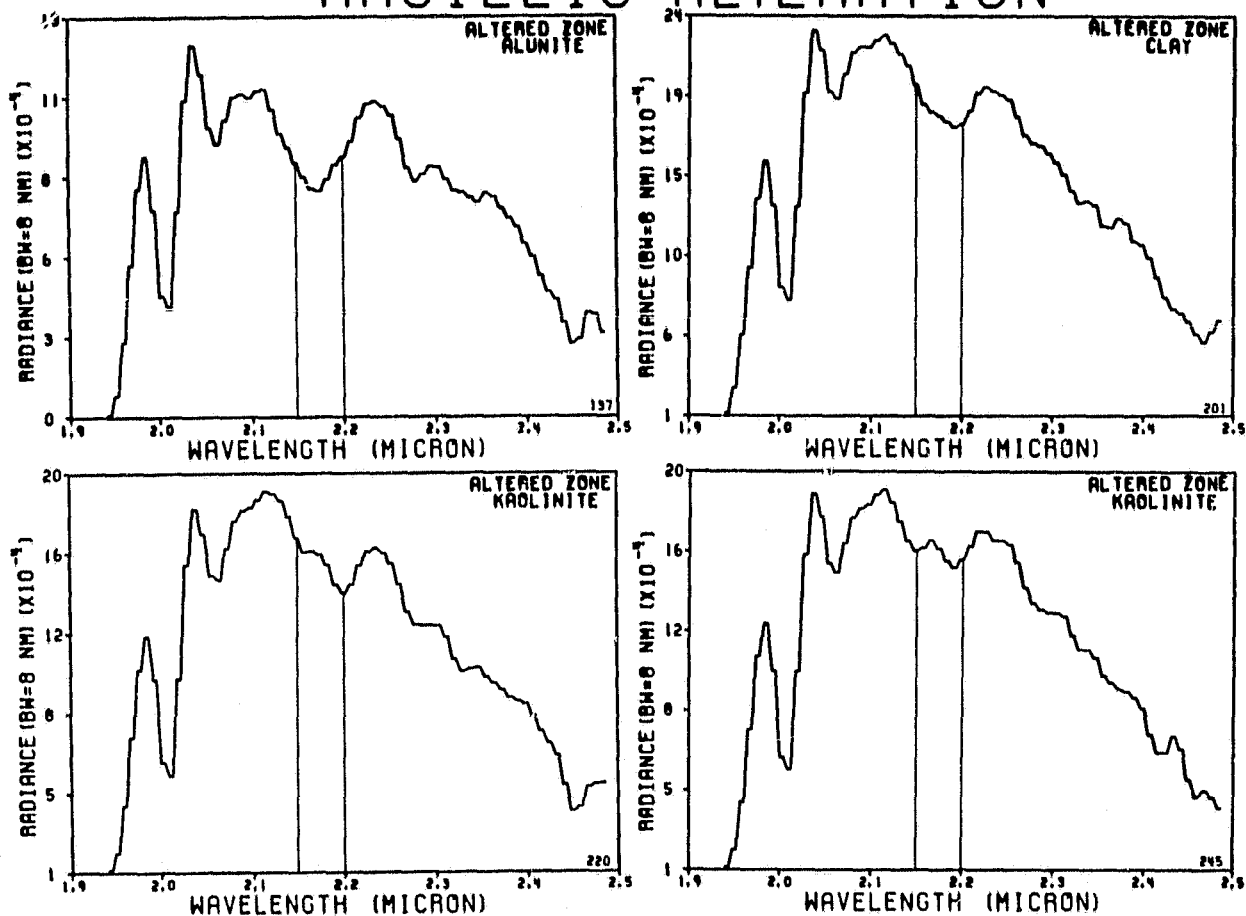


FLIGHT LINE GF2

Figure 15. Spectral curves from measurements 60, 61, 108, and 120 along traverse GF2. Spectra are from the background, unaltered, area and from within the alteration zone.

ORIGINAL PAGE IS
OF POOR QUALITY

GOLDFIELD DISTRICT ARGILLIC ALTERATION



FLIGHT LINE GF2

Figure 16. Spectral curves from measurements 137, 201, 220, and 245 along traverse GF2, Goldfield. Spectra are from within the alteration zone.

Cuprite Survey

The hydrothermal alteration in the Cuprite district is mapped in Figure 17. Five traverses were flown over the site. The data from flight line CP-2, flown from the north to the south are shown in Figure 18. The Cuprite data shows a very close correlation with ground mapping of the opalized and silicified zones.

The data along flight line CP-2 were analyzed on the computer by a simple technique that considers all spectral bands in the 2.14 and 2.25 micron window. The upper left plot of Figure 18 shows the wavelength position of the minima of any absorption bands in this spectral window. The clay minerals are indicated by a minimum between 2.16 and 2.22 microns. The spectroradiometer traverse starts in the mapped opalized zone and shows a clay feature up to measurement 30 where the unaltered tuffs and a small silicified zone are crossed. The data show mostly a 2.25 minimum out to measurement 45 where the traverse passes again into the opalized zone. The traverse crosses a ridge of silicified rock at about measurement 55 and then gets back into the silicified zone at about measurement 75. The correlation between the mapped alteration and the minimum shift is very close in the survey area.

The spectra in Figure 18 show very strong features of apparent alunite and kaolinite mineralization in the opalized zone. The spectrum from the silicified zone shows no clay, but it does show possible carbonate. The weak 2.175 micron feature and the

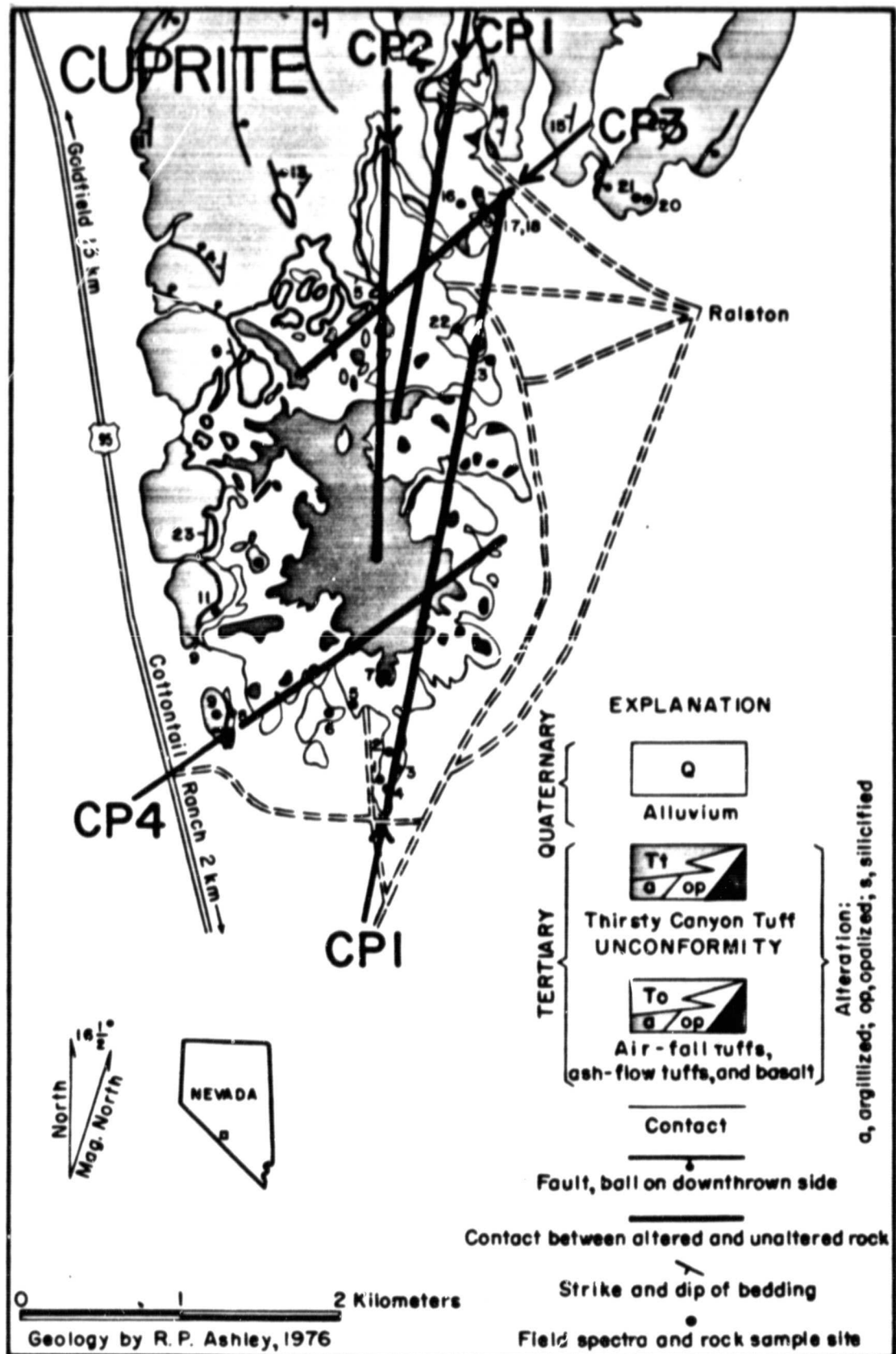


Figure 17. Geologic map of the Cuprite district from R.P. Ashley, 1976. Heavy lines indicate aircraft traverses flown. Traverse CP2, data is presented in Figure 18.

ORIGINAL PAGE IS
OF POOR QUALITY

CUPRITE DISTRICT SILICIC / ARGILLIC ALTERATION

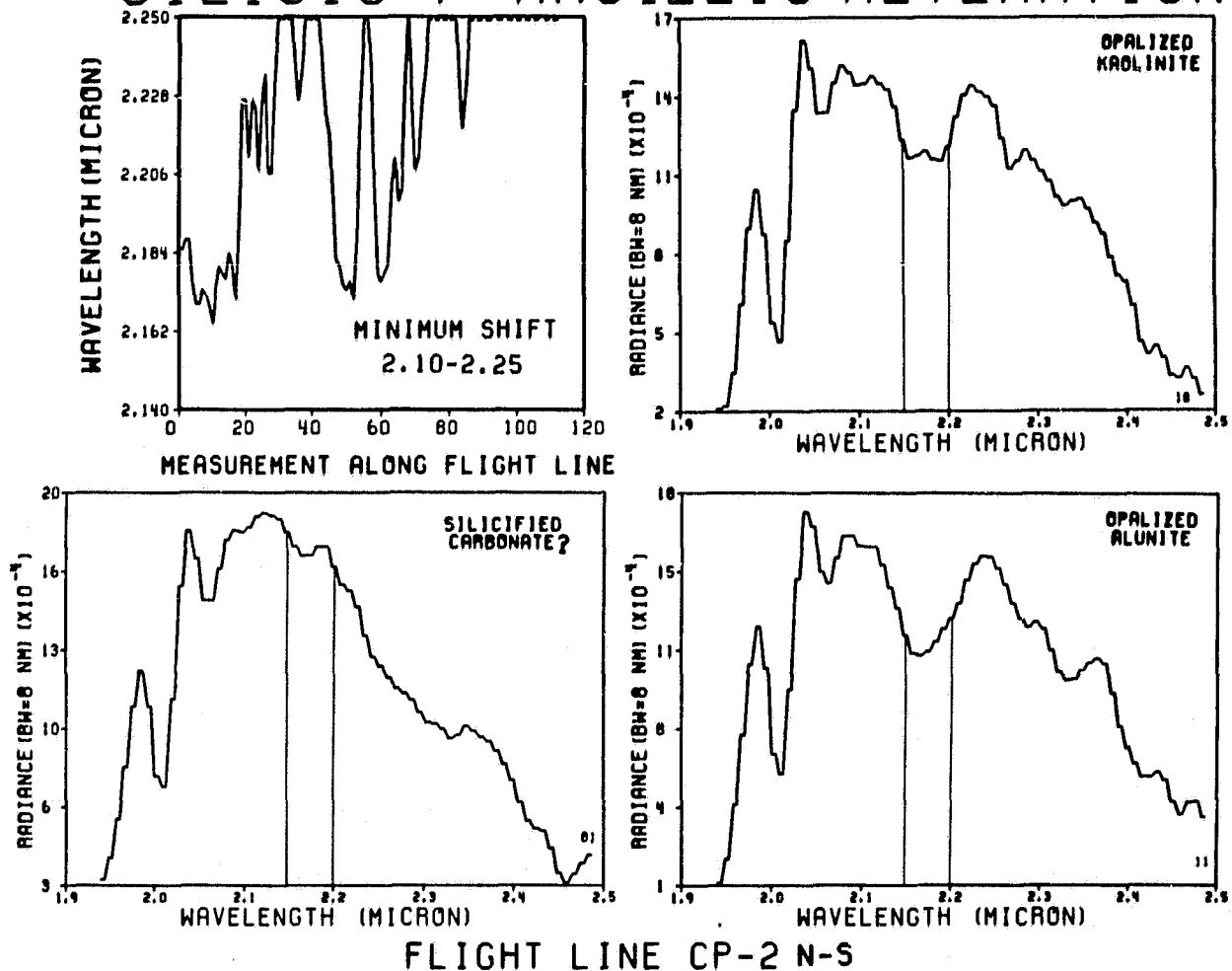


Figure 18. Minimum shift analysis and spectral curves from traverse CP-2, Cuprite. The alunite and kaolinite bands are very strong in the Cuprite data.

broad 2.3 micron feature appear very similar to the carbonate spectral features in Figure 23. Ground sampling and spectral measurements are needed to determine specifically the minerals responsible for the 2.3 micron features in the silicified alteration area.

Silver Peak Survey

The Silver Peak survey lines in Emerald County, Nevada, were flown to study various rock units shown in Figure 19. Flight line SP1 traverses an ash flow tuff. Traverse PM1 was flown over a green phyllite. Flight line L1 starts over a granitic intrusive, crosses a marble unit, and ends in alluvium.

Typical spectra from the first two traverses are shown in Figure 20. The typical volcanic tuff spectra from traverse SP1 are shown on the right. The tuff unit spectra are very consistent across the entire rock unit. They show weak bands at 2.1, 2.15, and 2.2 microns. There is a strong shoulder at 2.25 microns, and weak bands at 2.3 and 2.33 microns. This signature is very distinctive at high spectral resolution. Ground sampling and spectral measurements are needed to identify the mineral.

The phyllite spectra from traverse PM1 are also very distinctive, and very consistent across the rock unit. The strong 2.2 and the weaker 2.35 micron bands are characteristic of muscovite (Hunt, 1979). The clear band at 2.28 and the weak band at 2.1 microns occur frequently in the survey spectra from many of the sites. The minerals

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

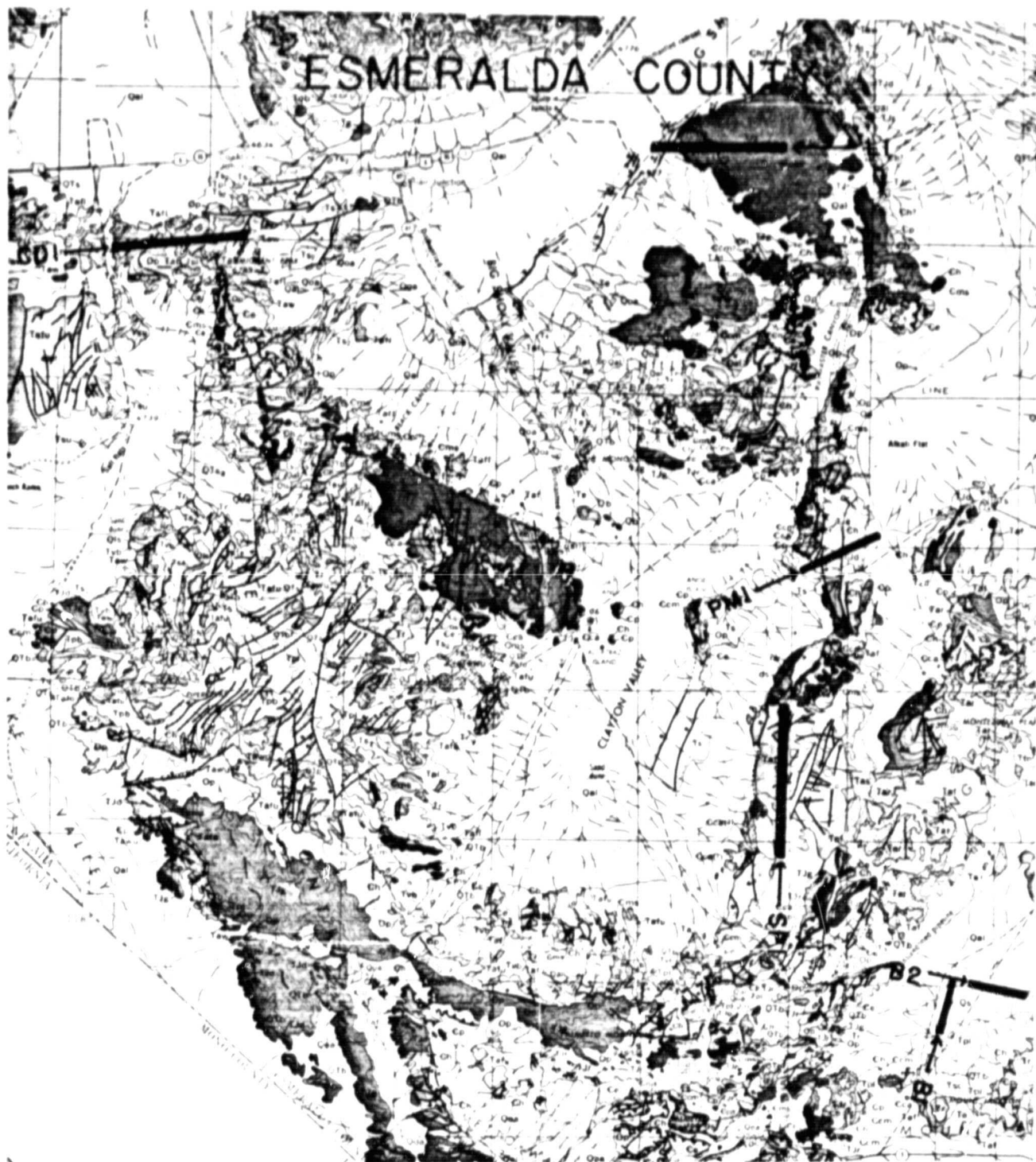


Figure 19. Geologic map of the Silver Peak area, Esmeralda County, Nevada. Traverses flown are SP1, PM1, and L1.

ORIGINAL PAGE IS
OF POOR QUALITY

SILVER PEAK ROCK UNITS

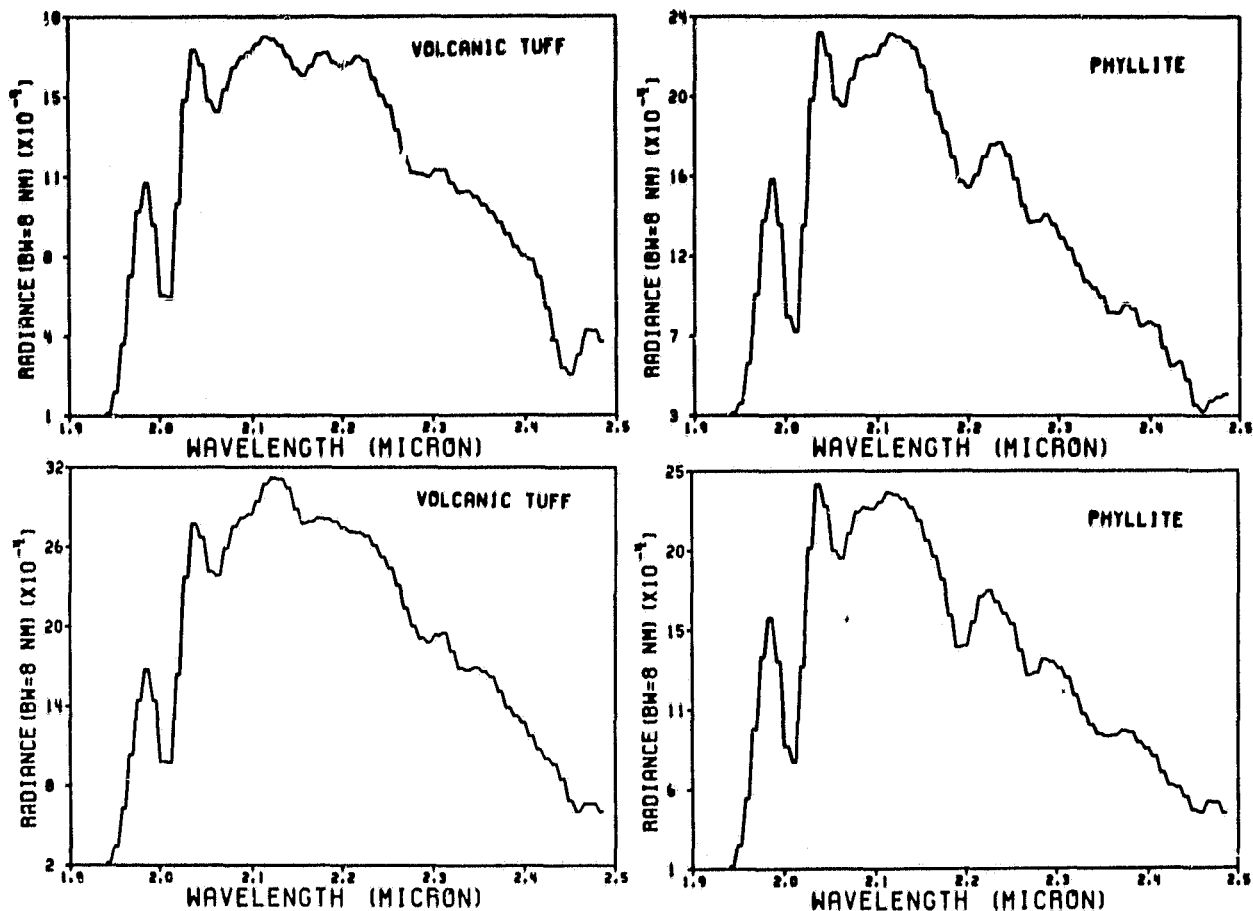


Figure 20. Spectral curves from traverses SP-1 and PM-1 in the Silver Peak area. The two rock units are distinctly different in the infrared spectral bands.

responsible are not identified at present. Ground spectral measurements and sampling are required again in this site.

The LM1 flight line was flown mainly to obtain spectral data from the marble unit, which would test the instrument sensitivity to carbonates. The waveform analysis results for this flight line are shown in the upper diagram of Figure 21. The waveform coefficient functions used for the clay features (functions 3/2, 1/4, and 4/5) do not work as well for the carbonates, but the coefficient function 5/1 was found to work very well. This indicates, again, that there is a large amount of information in this infrared spectral region, and that specialized pattern recognition techniques are required to extract the mineralogical information.

The coefficient 5/1 function is at about 1.555 over the igneous rock unit. Over the marble there is a large increase indicating a very clear spectral difference. The coefficient 5/1 function for Goldfield flight line 25, and the Mud Lake traverse, are shown in the lower diagram. The background value for both Goldfield and Mud Lake are about 1.555, similar to the igneous unit. In the clay alteration areas the 5/1 function drops below background. These analysis results indicate a clearly discernable spectral difference between clay and carbonate units, and one that can be mapped with the airborne system.

ORIGINAL PAGE IS
OF POOR QUALITY

LONE MOUNTAIN WAVEFORM ANALYSIS

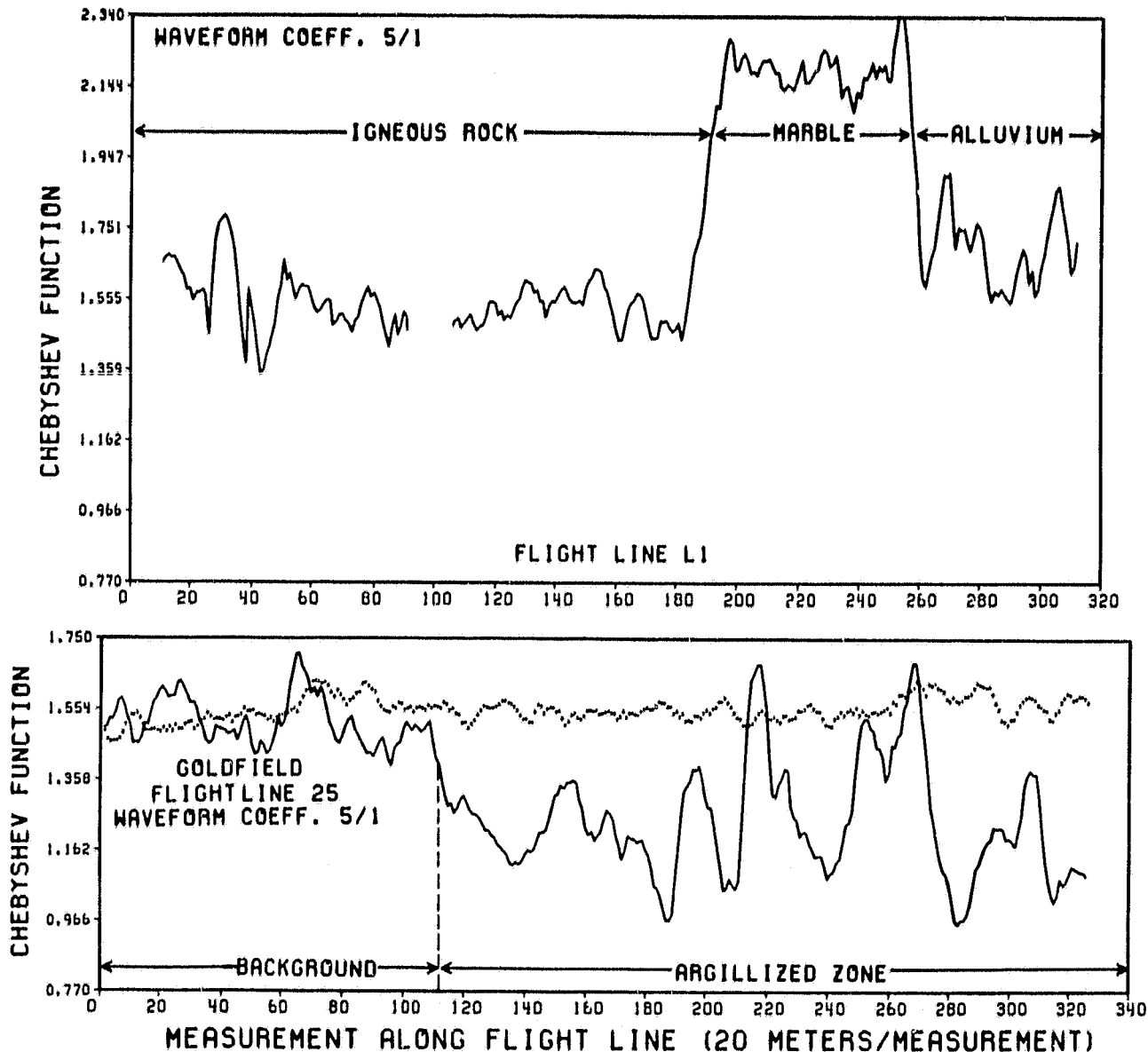


Figure 21. Traverse L1 analysis showing spectral contrast between igneous rock unit and carbonate. The waveform analysis using coefficient 5/1 on flight line 25, Goldfield, is included to show also the contrast between carbonates and clays.

Spectra from flight line L1 are shown in Figures 22 and 23. The spectra from the igneous intrusive show weak clay doublet bands and some weak 2.2 micron bands. The marble spectra have a strong carbonate band with a sharp shoulder at about 2.23 microns and a well defined minimum at about 2.33 microns. The coefficient 5/1 ratios indicate that weak carbonate features are still visible in the alluvium below the marble outcrop. The alluvium spectra show clay bands in the 2.15 to 2.2 microns region and apparent weak carbonate bands at wavelengths longer than 2.2 microns.

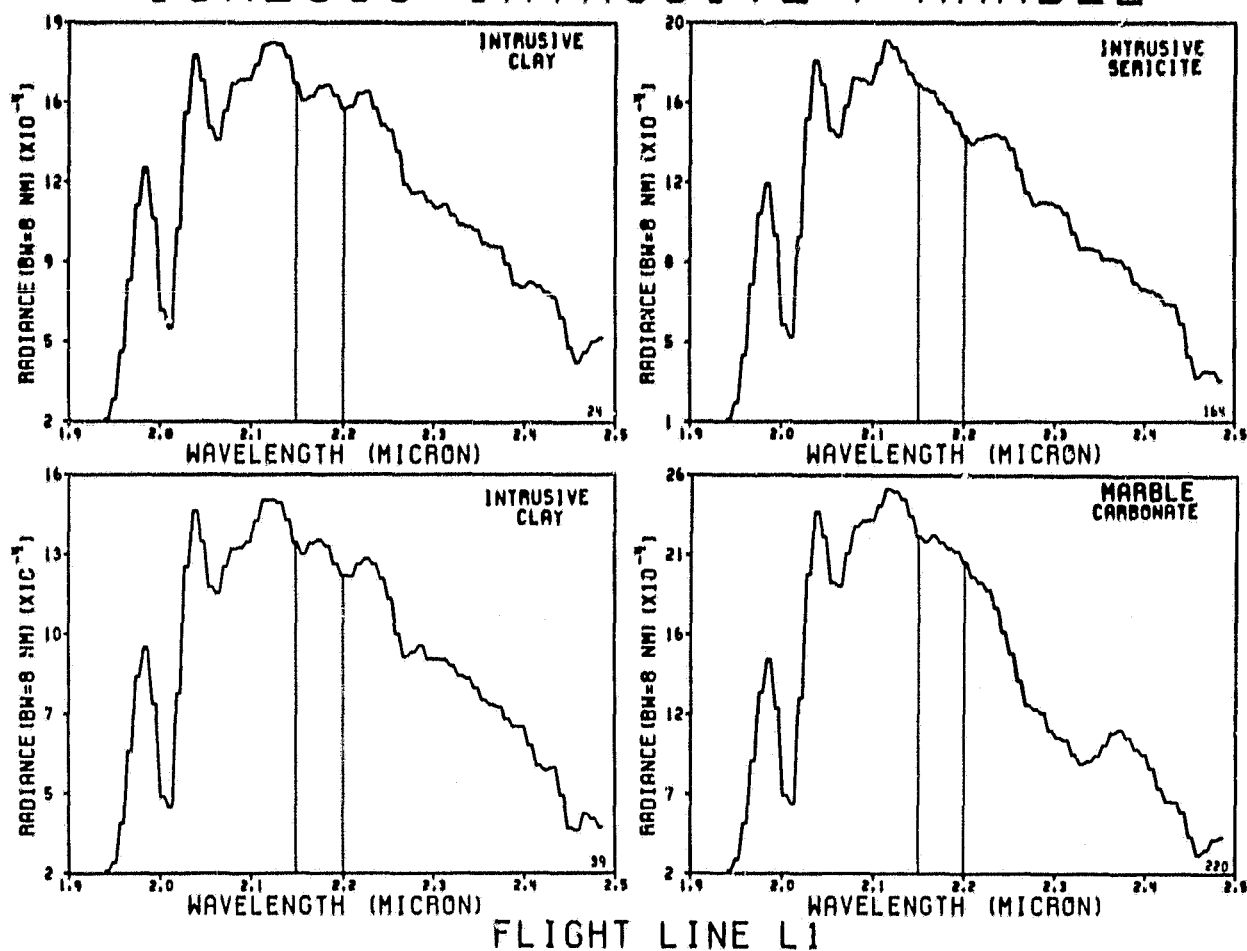
Candelaria

The Candelaria traverse, shown in the aerial photo of Figure 24, begins in a light colored volcanic unit that is hydrothermally altered. It passes into alluvium and dark colored meta-sediments to measurement 250 where the traverse crosses a light colored unit that is known from ground mapping to be unaltered, but high in muscovite.

The waveform function 5/1, found useful for the Lone Mountain data analysis, also produces very good results in analysis of the Candelaria data. The results are shown in Figure 25. The bottom diagram of Goldfield and Mud Lake data show values of 1.555 for background areas, and lower values over the argillic mineral zones. The data from the Candelaria traverse shows low values over the altered volcanics from measure-

ORIGINAL PHOTO COPY
OF POOR QUALITY

LONE MOUNTAIN IGNEOUS INTRUSIVE / MARBLE



FLIGHT LINE L1

Figure 22. Spectral measurements 24, 39, 164, and 220 from traverse L1 in the Silver Peak area. The distinct carbonate band is shown in the lower right spectrum.

ORIGINAL FIGURE
OF POOR QUALITY.

LONE MOUNTAIN IGNEOUS INTRUSIVE / MARBLE

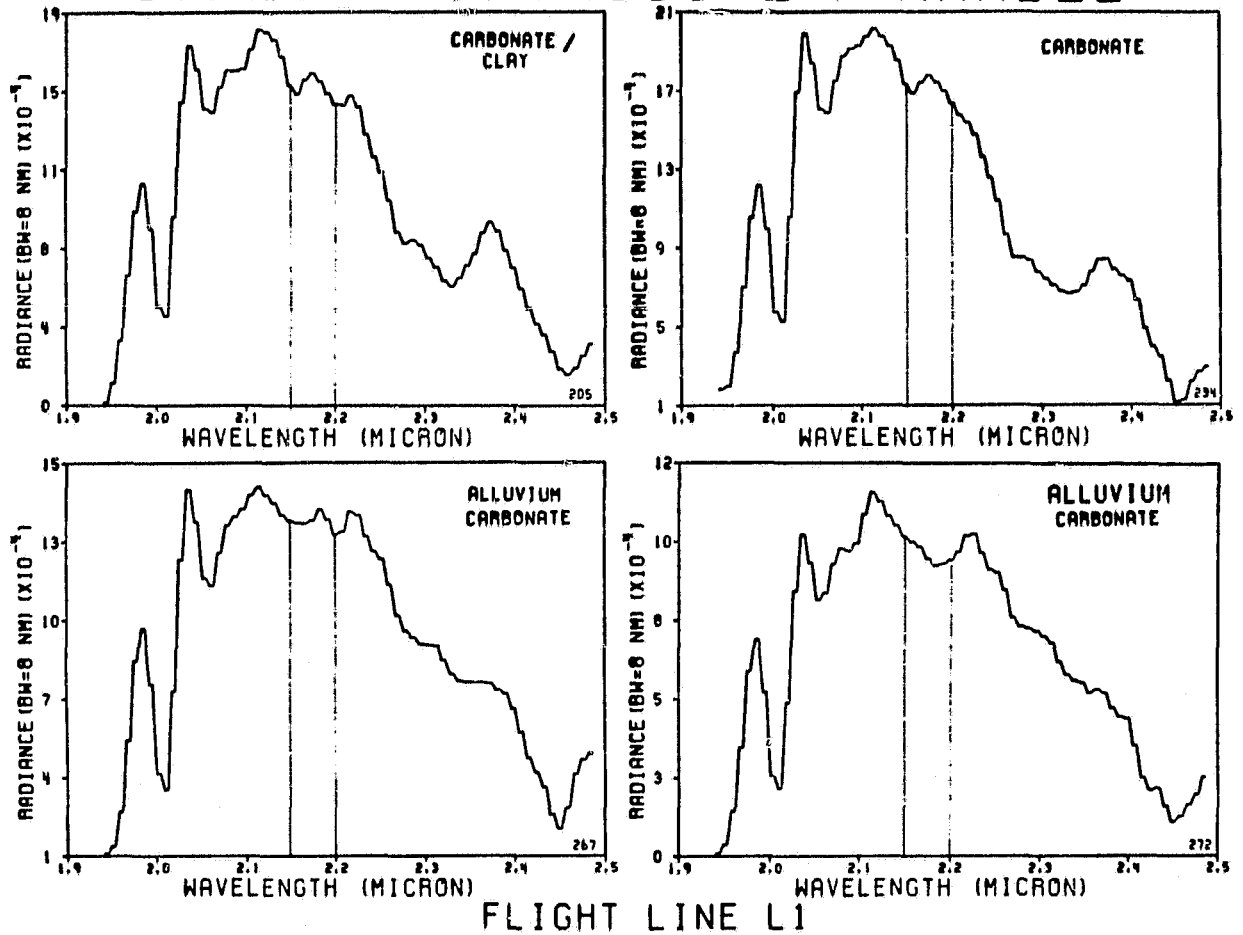


Figure 23. Spectral measurements 205, 234, 267, and 272 along the L1 traverse, Silver Peak area.

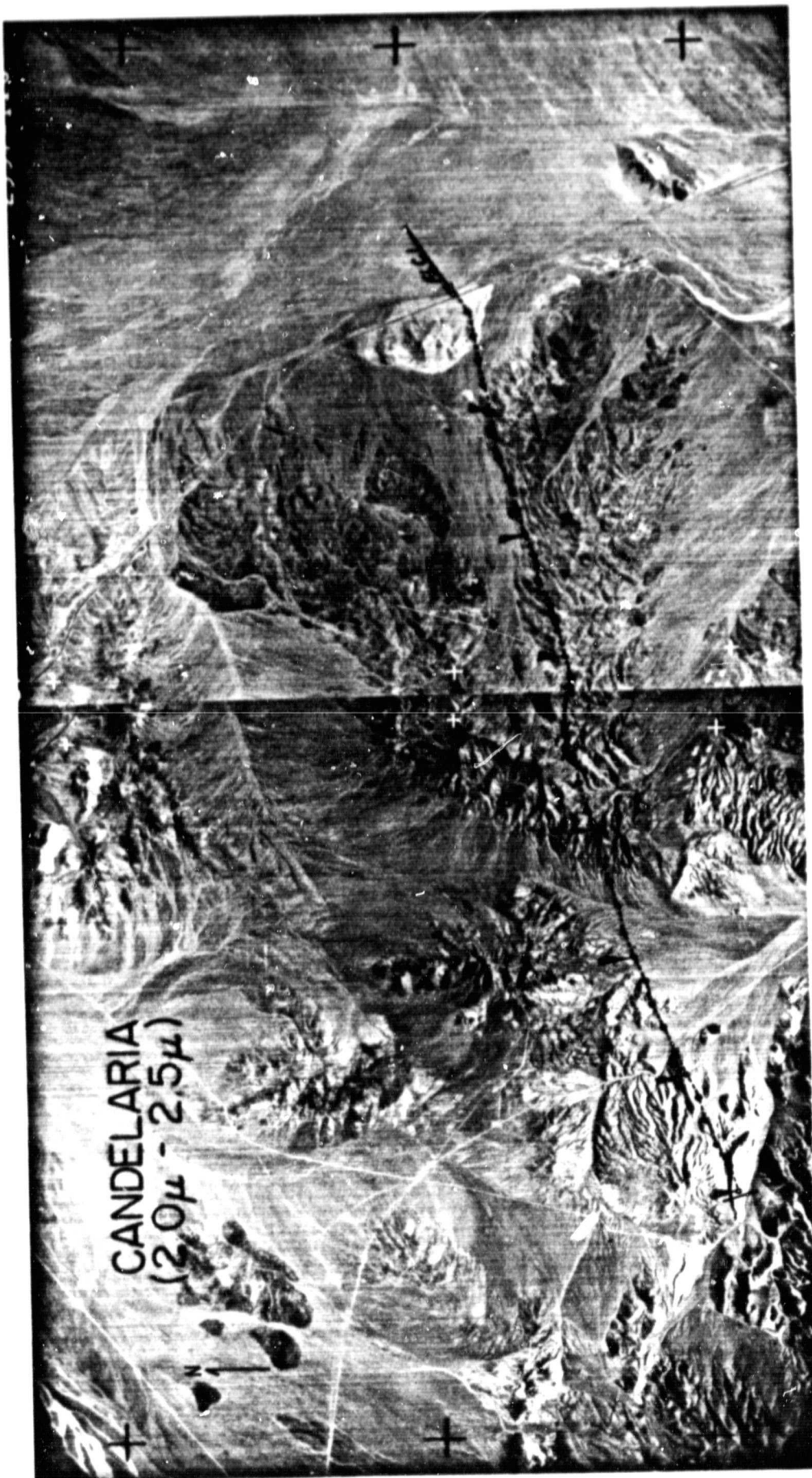


Figure 24. Aerial photographs of Candelaria site. Dashed line shows aircraft ground track for traverse C1. Small circles mark the location of every tenth spectral measurement.

CANDALARIA WAVEFORM ANALYSIS

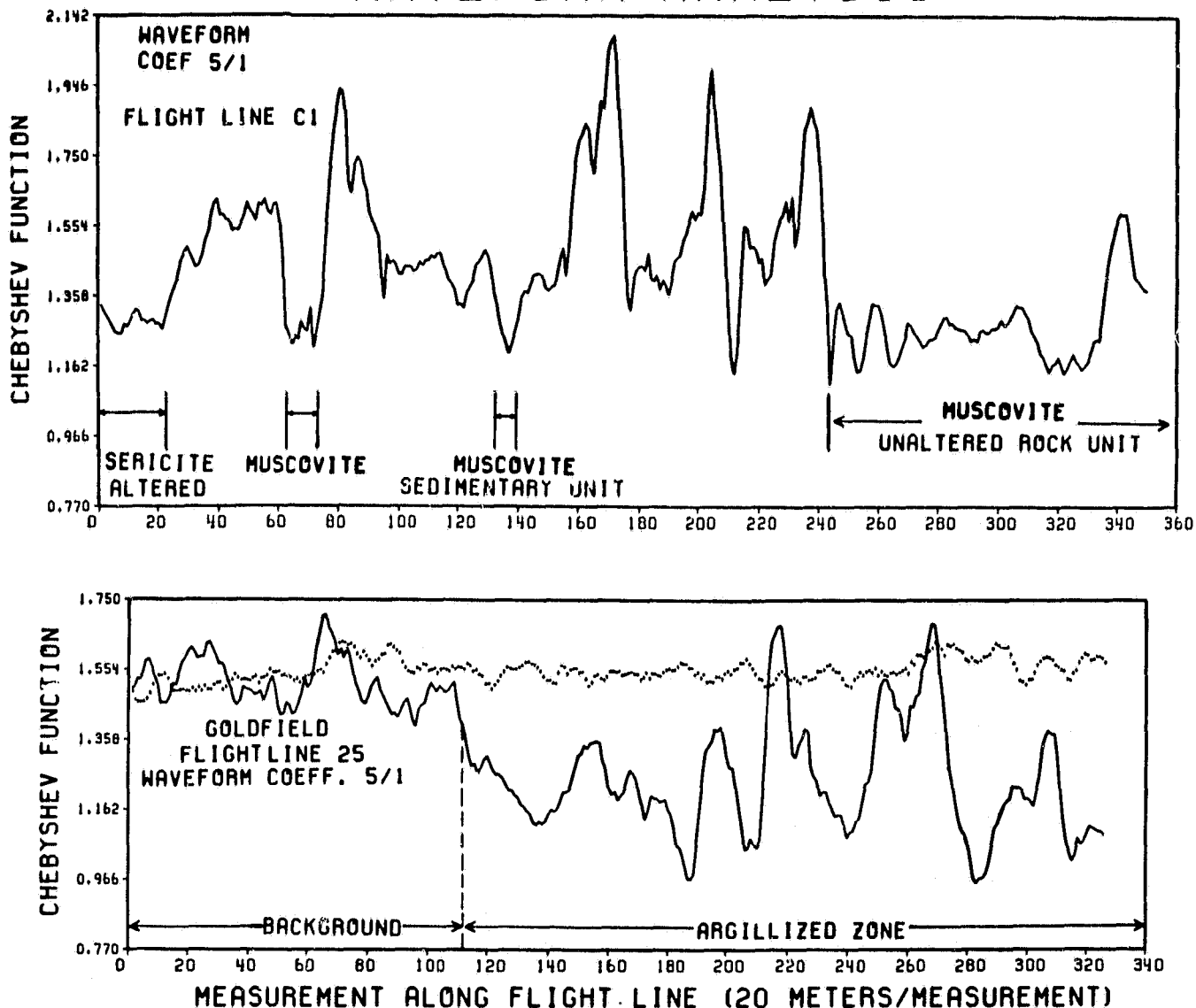


Figure 25. Traverse C1 in the Candalaria test site. Waveform analysis is done using coefficient 5/1 function. Same analysis on Goldfield flight line 25 is shown for reference. Dotted curve in lower diagram is waveform function 5/1 analysis on the Mud Lake data.

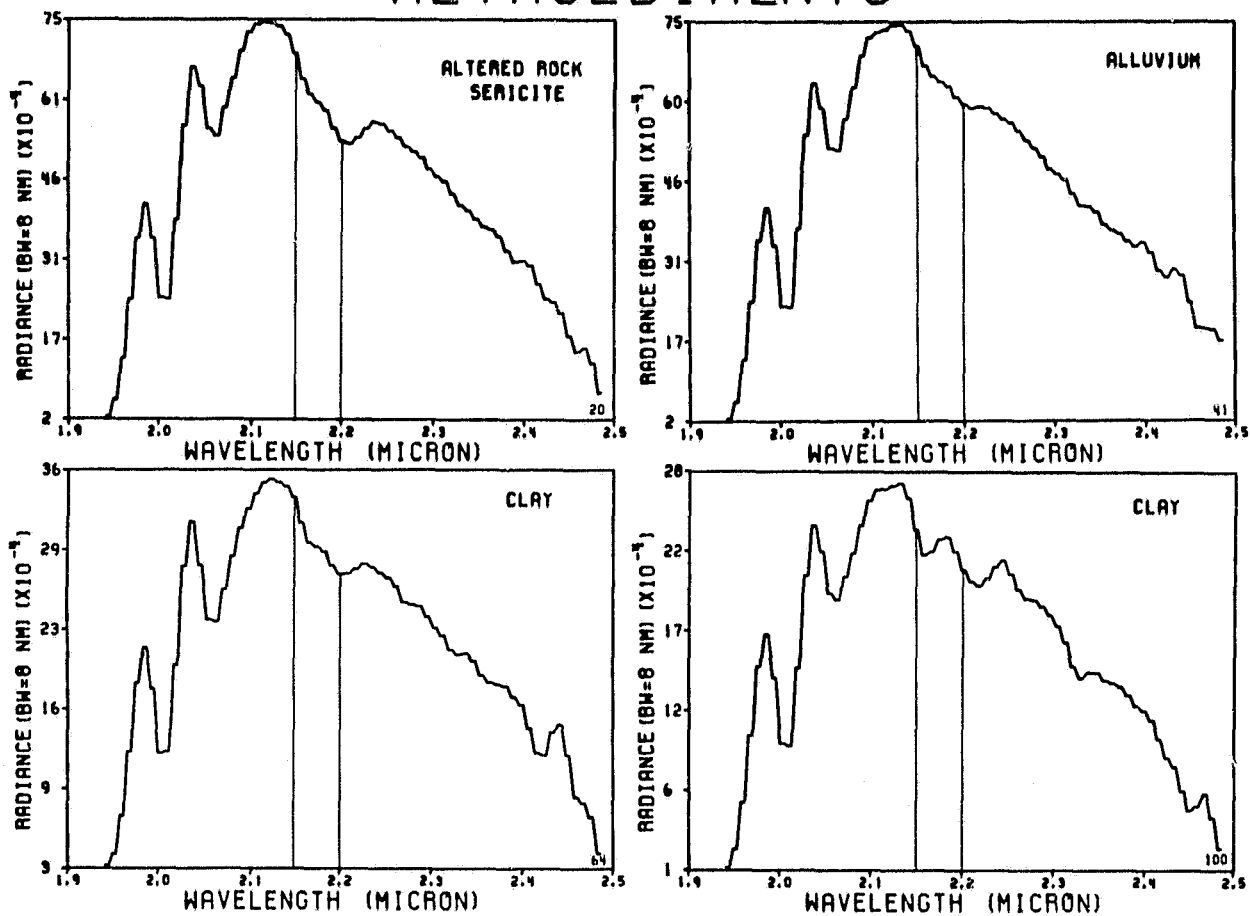
ment 1 to 20 and beyond measurement 240 where the rock unit is known to be high in muscovite. Several other zones in the metasedimentary unit appear to contain significant muscovite, which would indicate shale or phyllite zones. Other areas have high coefficient 5/1 values indicating possible carbonate zones in the metasedimentary unit. Ground reconnaissance and sampling are required to follow up these results and to establish lithologic mapping techniques.

Selected spectra from the Candelaria traverse are shown in Figures 26 and 27. Spectrum 20 from the altered area shows a distinct 2.2 micron feature of sericite. Spectrum 41 is from the alluvial zone as can be seen in the photo of Figure 24. There is little clay absorption in the spectral curve. The waveform values in Figure 25 correctly classify the area around measurement 41 as background, or weak absorption in the mineral bands.

The spectrum from measurement 64 has a moderate feature at 2.2 microns. This area was apparently correctly identified as high in muscovite judging from the low waveform values in Figure 25. The mineral band in spectrum 100 is a doublet indicating a different mineralogy than muscovite alone. The area near measurement 137 was also identified as having muscovite mineralogy according to the waveform values in Figure 25. The spectral curve for measurement 137 in Figure 27 shows a very sharp 2.2

ORIGINAL PAGE IS
OF POOR QUALITY

CANDALARIA METASEDIMENTS



FLIGHT LINE C1

Figure 26. Spectral curves for measurements 20, 41, 64, and 100 along traverse C1, Candelaria.

CANDALARIA METASEDIMENTS

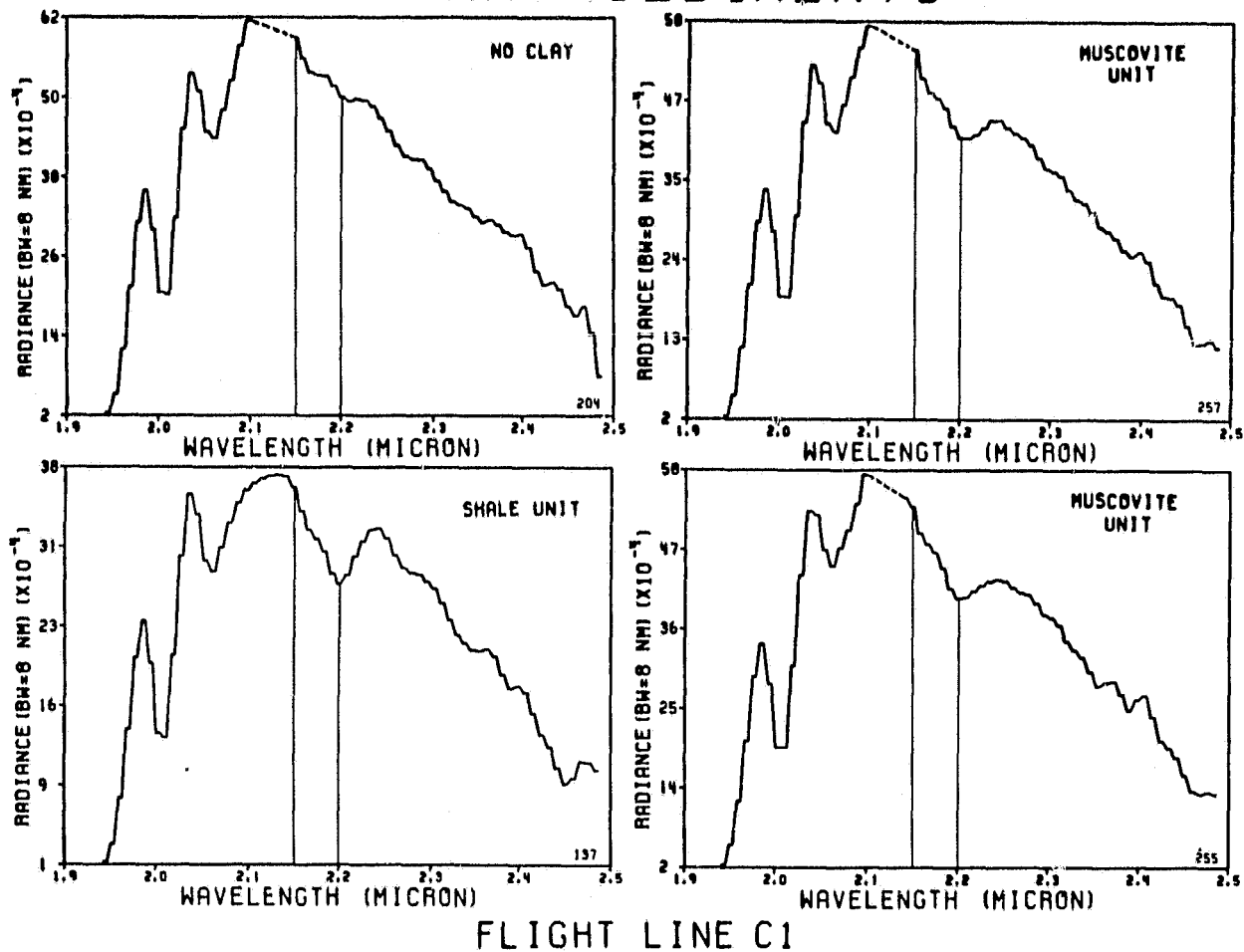


Figure 27. Spectral curves for measurements 204, 137, 257, and 255 along traverse C1, Candelaria.

micron band similar to the mineral feature observed in the phyllite zone of the Silver Peak traverse PM1. Spectra 255 and 257 show 2.2 micron absorption bands of muscovite, which correlates with the known mineralogy of this rock unit from previous ground mapping by the U.S. Geological Survey.

The Candelaria data were analyzed further using the minimum shift technique and band ratios (Figure 28). The minimum shift data show 2.2 micron minima in the areas mapped as altered volcanics and unaltered muscovite unit. Zones near measurements 64 and 137, which were classified as muscovite mineralogy, as well as some other zones in the metasediment unit, show a 2.2 micron absorption minimum. The minimum shift analysis shows no mineralogy with bands at shorter wavelengths than 2.2 microns. This is in contrast to the Goldfield spectral data (Figure 9) and Cuprite data (Figure 18) that show strong shifts toward 2.15 microns in areas of hydrothermal alteration minerals.

Among the analysis techniques applied to the Candelaria data, the waveform results clearly show the best contrast in mineralogy. The minimum shift technique also works well. The band ratio technique, using bands chosen in Figure 2, and plotted in the two lower curves of Figure 28, do not produce good contrast among the rock units along the Candelaria traverse. The band ratios are more limited in spectral information because fewer data points are put into the analysis, and because the bands

OF POOR QUALITY

CANDALARIA DISCRETE BAND ANALYSIS

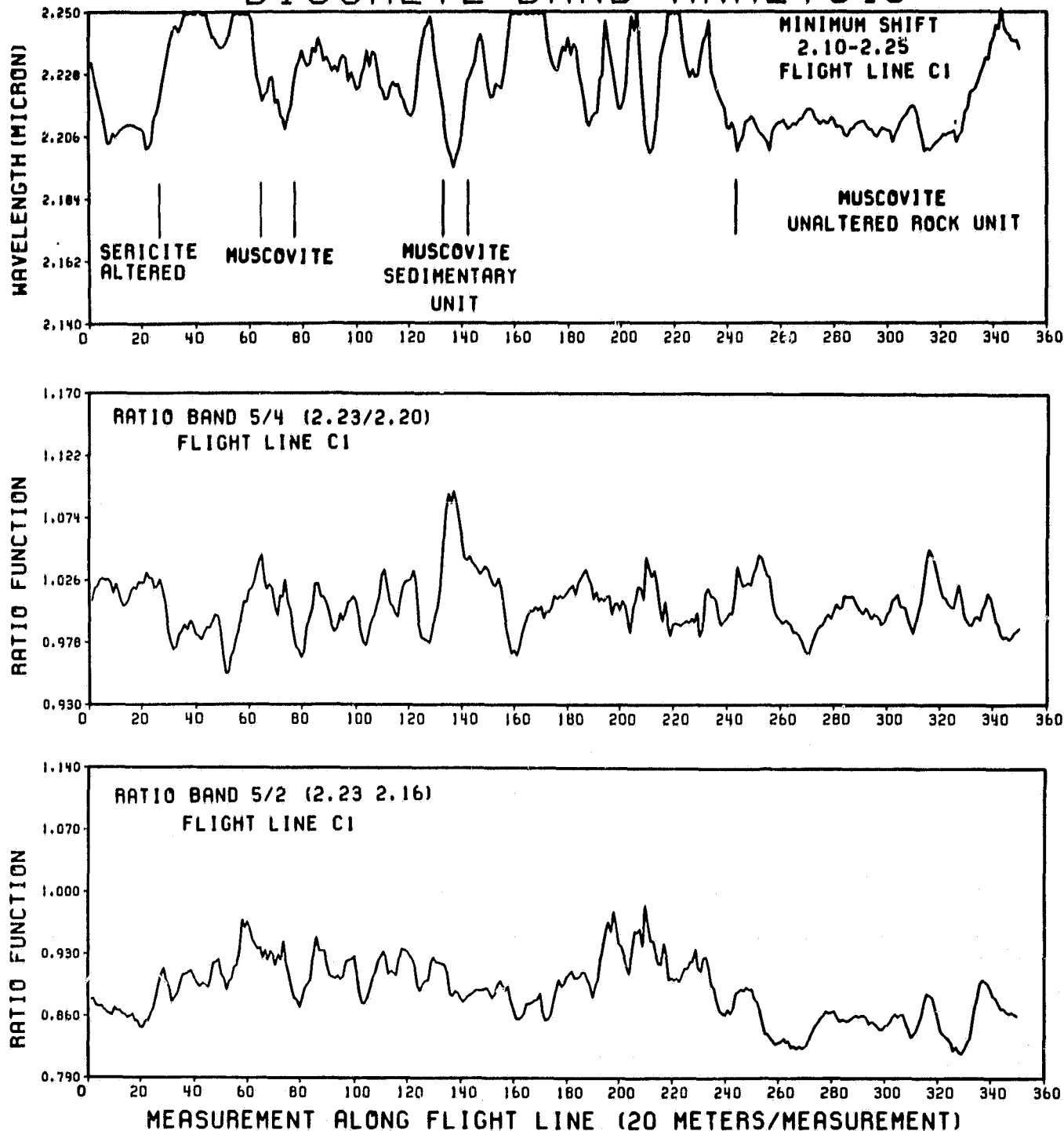


Figure 28. Minimum shift analysis and band ratio 5/4 and 5/2 analysis along traverse C1, Candelaria.

must be individually adjusted for each particular mineral. The band ratio contrasts are also solely dependent on the absorption intensities, where the waveform techniques are more sensitive to the spectral information, i.e. spectral positions of features.

Gillis Range

Two traverses from the Gillis Range site are included in the present analysis. Flight line GV2B traverses an alteration zone with mainly silicic alteration (Figure 29). Flight line GV2A traverses the zone to the southeast of GV2B. The hydrothermal alteration in this zone is mainly argillic as determined by U.S. Geological Survey mapping.

The data in this area are analyzed with the techniques used in the Cadelaria site. In this case the band ratio technique has yielded much better results. The flight line GV2B results shown in Figure 30 indicate several zones of sericitic mineralization along the traverse. The mineral band minima are at 2.2 microns with no shifts toward shorter wavelengths that would indicate clay alteration species other than sericite. The spectral data correlate well with the geologic mapping, which shows silicic mineralization.

The spectral curves along traverse GV2B (Figure 31) show very strong 2.2 micron absorption bands in the zones labeled "sericitic" in Figure 30. Some spectra have kaolinite like

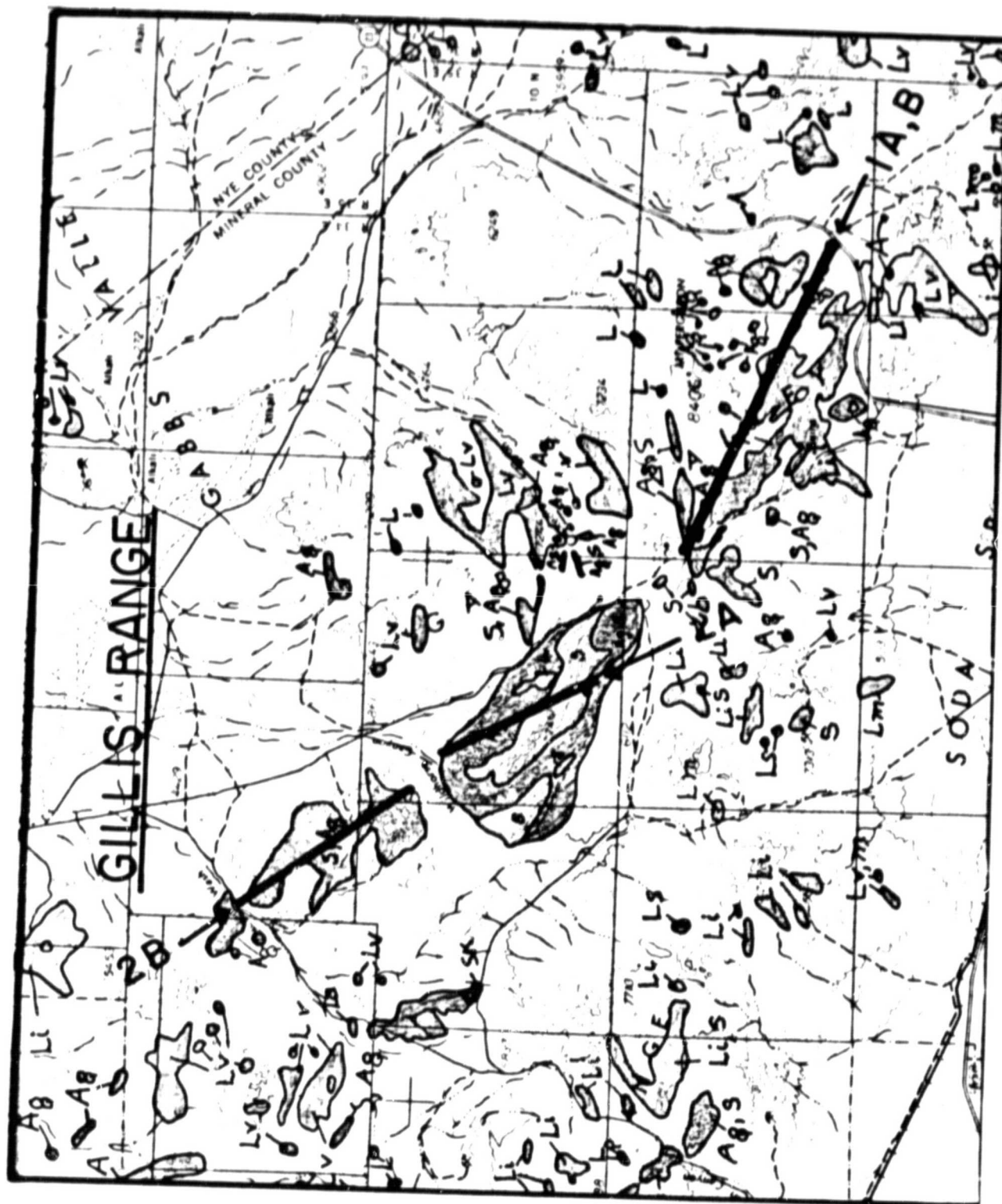


Figure 29. Geologic map of the Gillis Range test site. The 2B line traverses a silicic, argillic alteration zone. The 2A line traverses mostly argillic alteration.

GILLIS RANGE DISCRETE BAND ANALYSIS

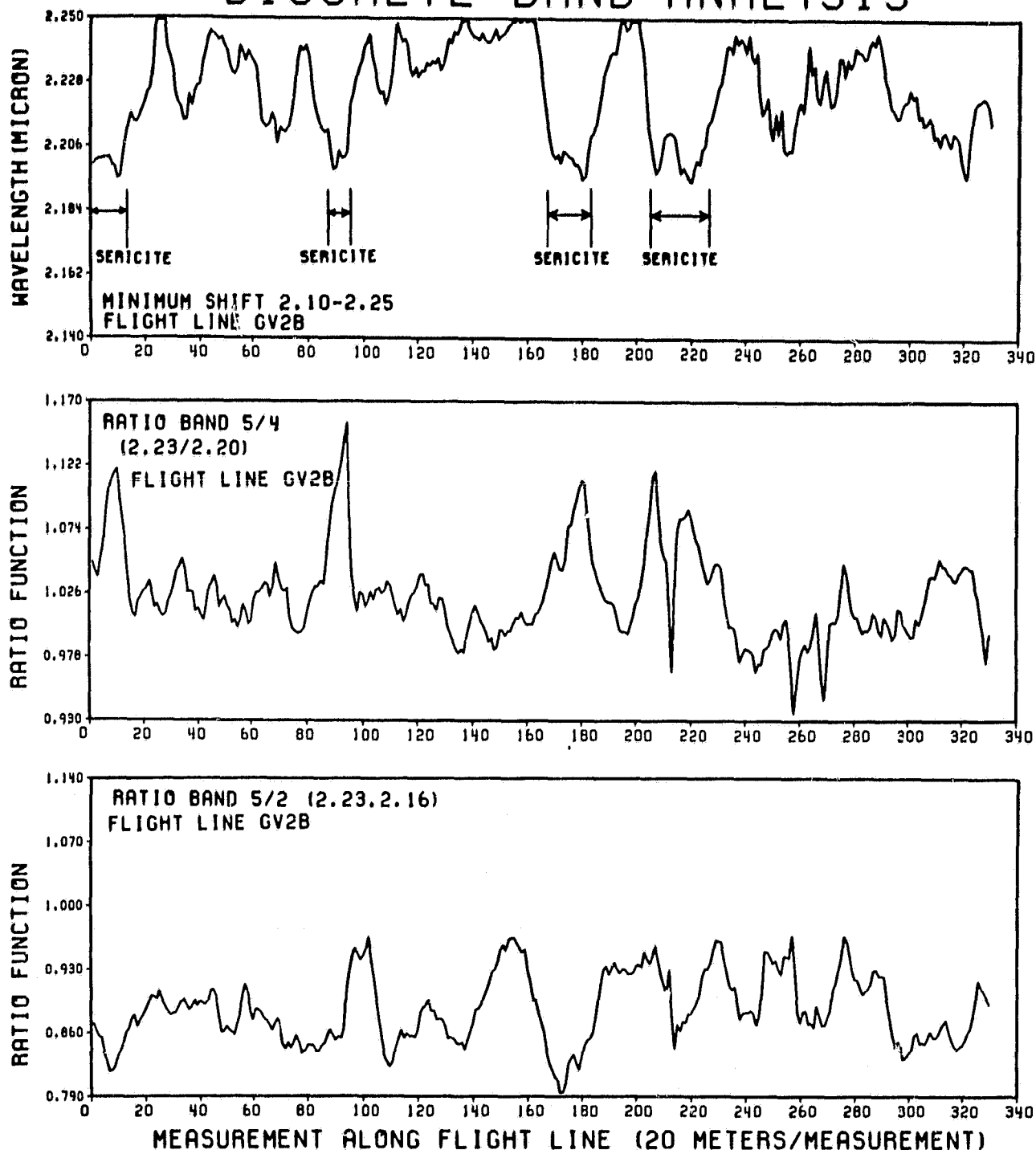


Figure 30. Traverse GV2B, Gillis Range, data analysis using the minimum shift and band ratio techniques.

ORIGINAL PAGE IS
OF POOR QUALITY

GILLIS RANGE SILICIC / ARGILLIC ALTERATION

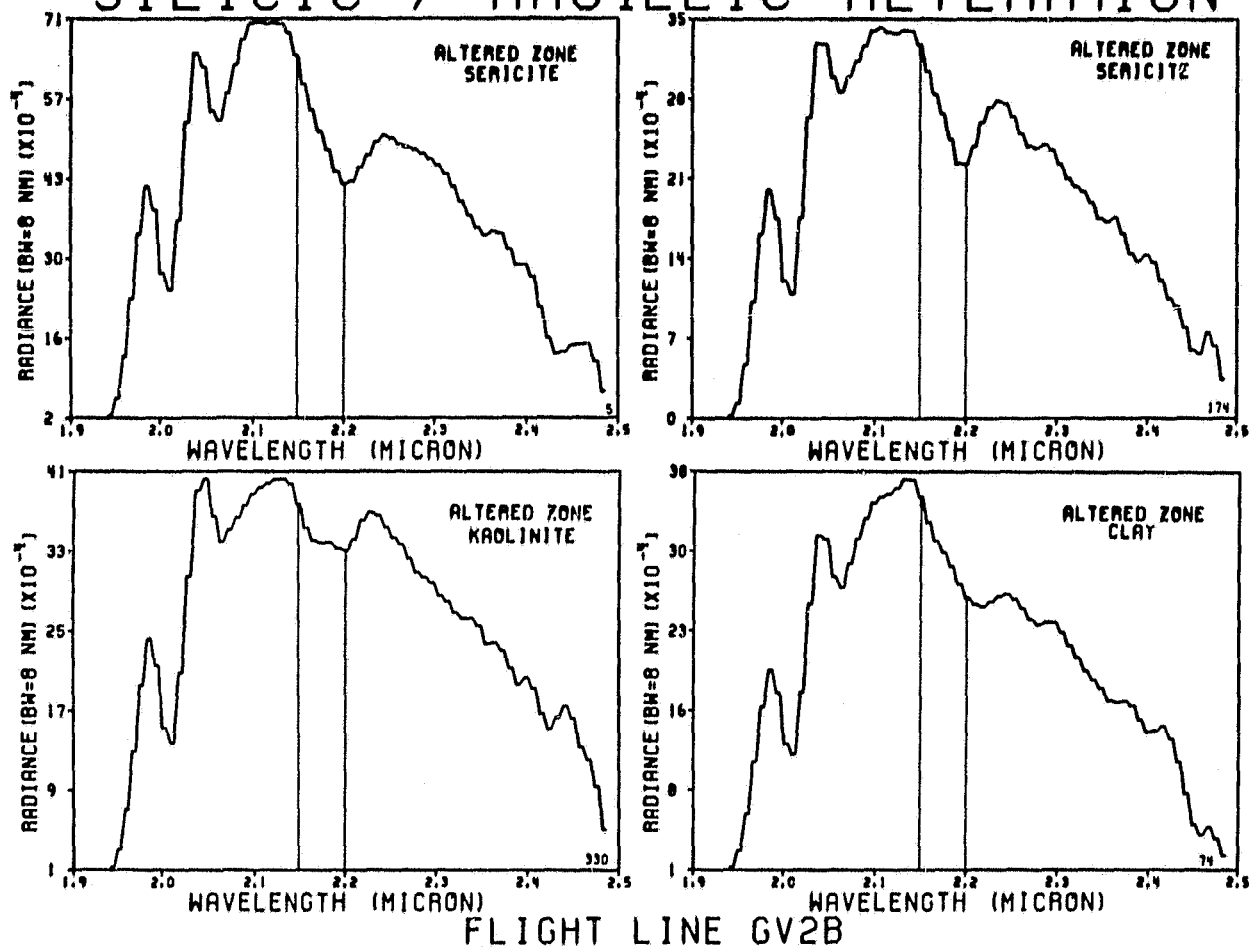


Figure 31. Spectral measurements 5, 174, 330, and 74 along the GV2B traverse, Gillis Range.

doublet features with the minimum also at 2.2 microns. The spectrum for measurement 74 shows a strong band with a minimum shifted to longer wavelengths than 2.2 microns. This spectral feature has been observed in data from other sites. Ground studies are required to determine the mineralogy that causes this spectral phenomenon.

The band ratio analysis for traverse GV2B correlates well with the minimum results and with the visually observed spectral features. The 5/4 ratios are higher in the sericitic zones indicating strong absorption at 2.2 microns. The 5/2 ratios are about the same as those for Candelaria, which indicates no detectable mineralogical difference between the two sites using the band 5/2 ratios.

The flight line GV2A data contrast quite sharply with traverse GV2B. This area is mapped as argillic alteration, which is also indicated in the analysis results of Figure 32. The minimum shift analysis on flight line GV2A indicates clay mineralization with absorption features near 2.16 microns. The band ratios also indicate strong absorption features in bands 2 and 4 at 2.16 microns and 2.2 microns. The ratios of bands 5/2 contrast sharply with the 5/2 ratios of flight line GV2B.

In the Gillis Range site the ratios of bands chosen from Figure 2 appear to work quite well. The 5/4 ratios are sensitive to the silicic mineralization along traverse GV2B. The 5/2

ORIGINAL PAGE IS
OF POOR QUALITY

GILLIS RANGE DISCRETE BAND ANALYSIS

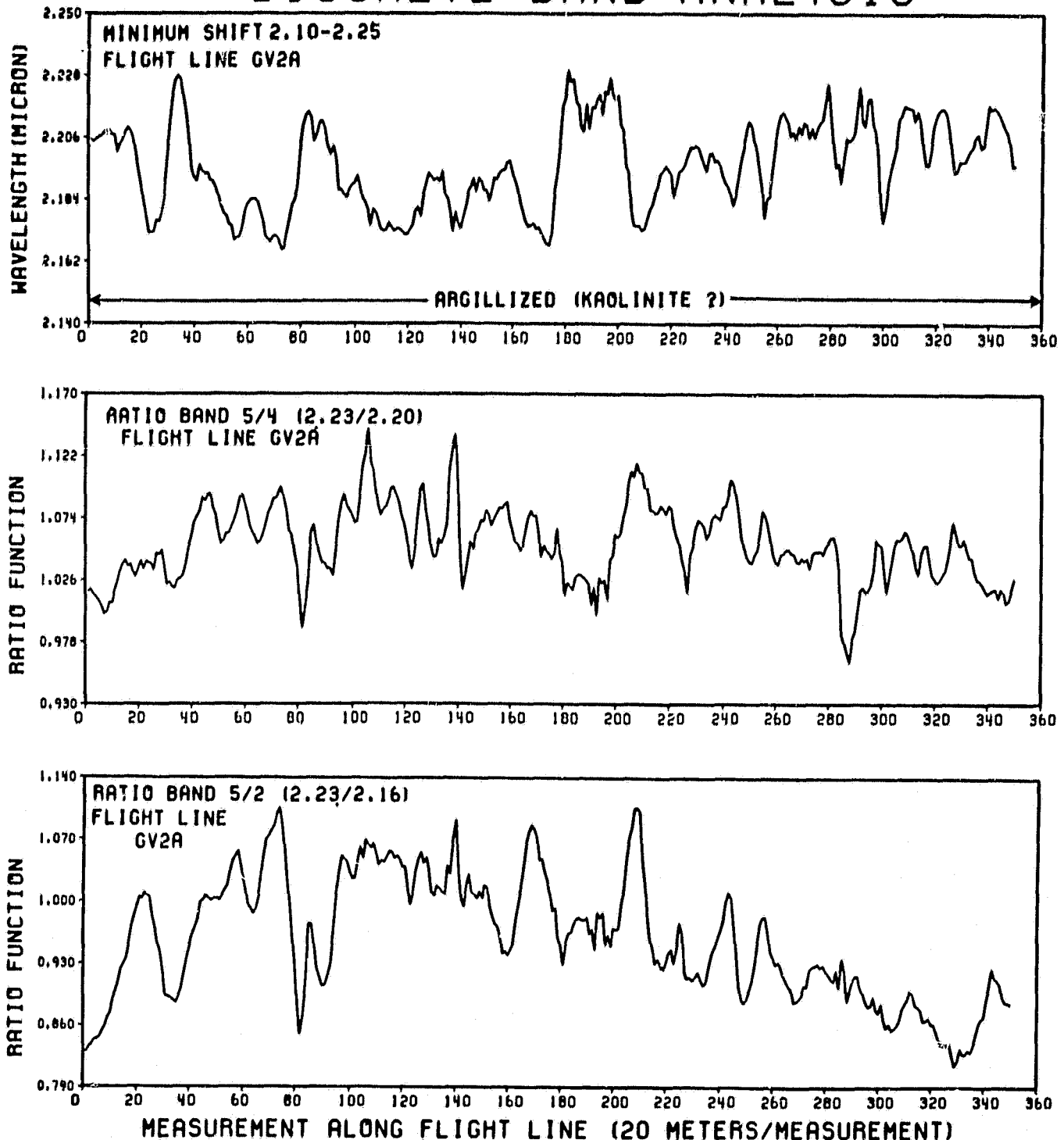


Figure 32. Traverse GV2A, Gillis Range, data analysis using the same minimum shift and band ratio techniques shown for traverse GV2B in Figure 30.

ratios clearly indicate the argillic zone and distinguish this type of alteration from the silicic alteration.

Jim Canyon and Sweet Water sites

The Jim Canyon site shown in Figure 33 is an argillic alteration zone. This site was covered with 10 to 50 percent vegetation and about 5 inches of snow. This site on LANDSAT imagery (Figure 5) appears as reddish vegetation cover. At 20 meter square fields-of-view, sufficient outcrop was visible to the airborne spectroradiometer to allow positive spectral identification of the alteration mineralization. Spectra from the JC1 traverse are shown in Figure 34. Kaolinite and sericite mineralization plus other clay or mixed clay mineralization appears quite clearly in the spectral measurements. The fields-of-view in these measurements all contain snow and vegetation as well as outcrop. The narrow infrared mineral bands, however, are unique to the minerals under the high spectral resolution. These features are therefore not masked by the presence of other materials in the instrument field-of-view. This is an important distinction between spectroradiometer capabilities as opposed to present imaging systems that would see only the very broad spectral region, in which case the data would most likely indicate snow or vegetation rather than clay mineralization.

ORIGINAL PAGE IS
OF POOR QUALITY

JIM CANYON ARGILLIC ALTERATION

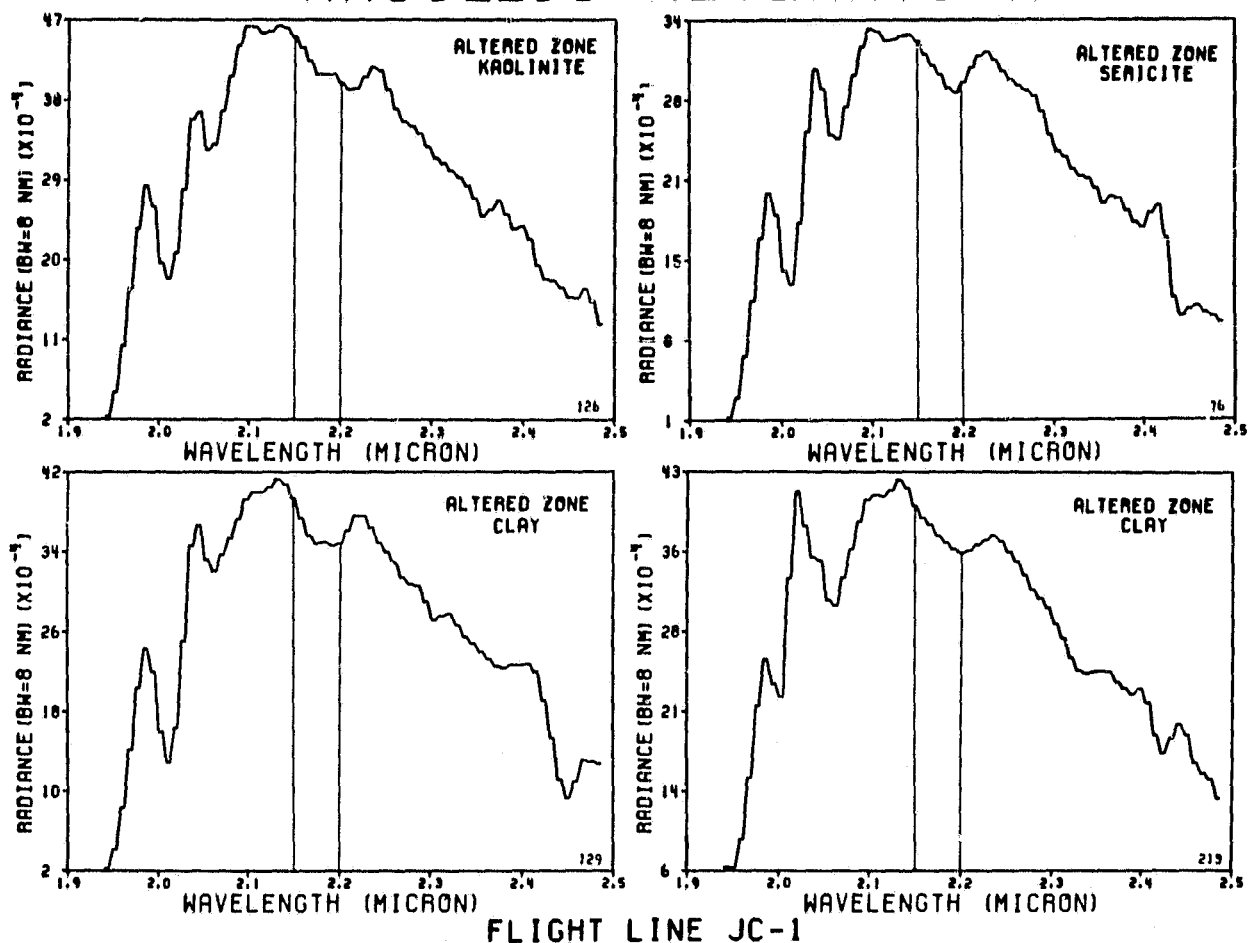


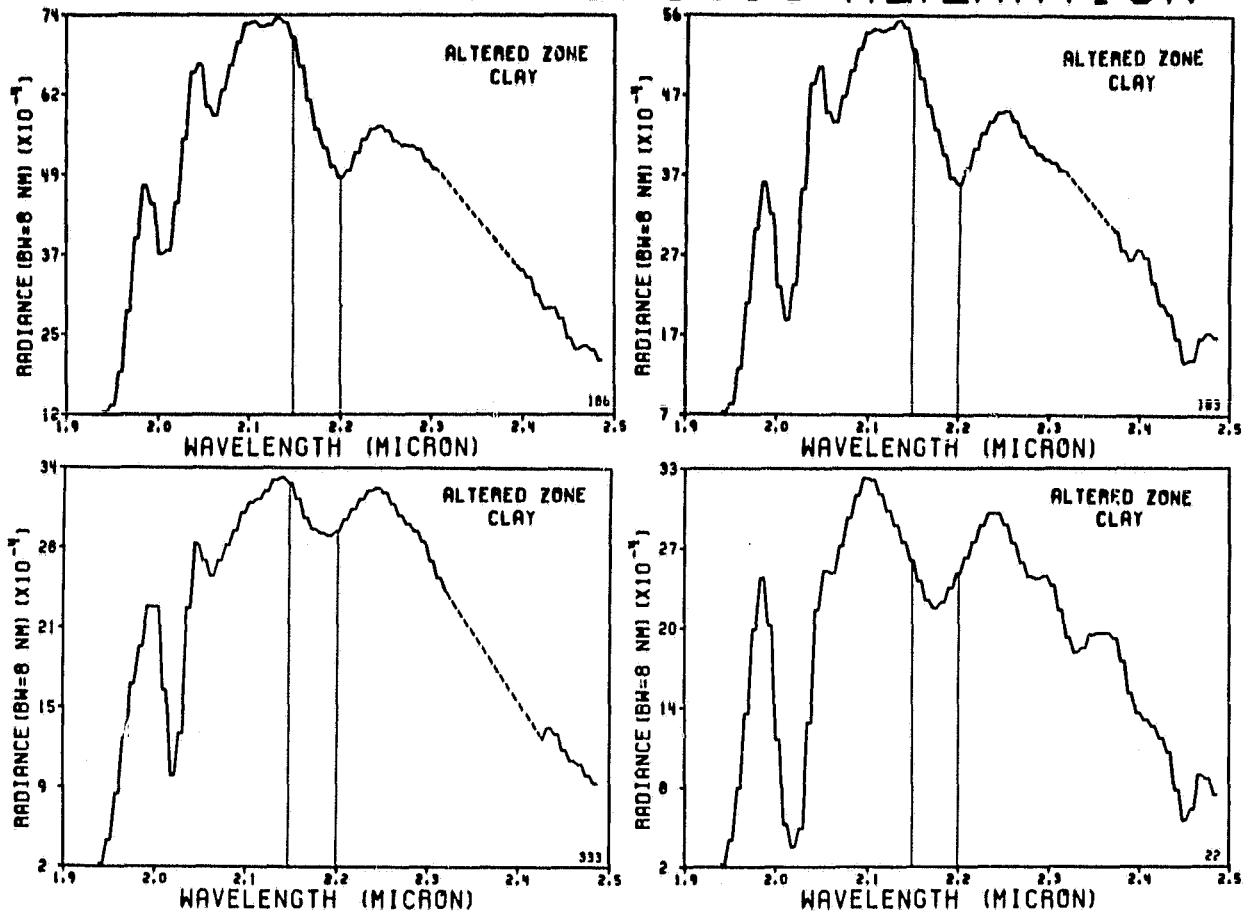
Figure 34. Selected spectral curves from the Jim Canyon traverse. Clay mineral bands are clearly present despite considerable vegetation and snow cover.

The Sweet Water site shown on Figure 35 is also mapped as an argillic alteration zone. The site is at the peak of a 12,000 foot mountain with near continuous snow cover, as seen on the LANDSAT image (Figure 5). The snow cover was approximately one foot at the time of the survey. Spectral measurements from traverse SW1 show very strong clay mineralization in the outcrop that protruded from the snow cover. The very deep 2.2 micron features indicate strong sericite mineralization. The deep band at 2.17 microns (lower right spectrum) and the other bands near 2.3 microns indicate strong alunite or other alteration clay mineralization.

57

ORIGINAL PAGE IS
OF POOR QUALITY

SWEETWATER MTN. ARGILLIC / SILICIC ALTERATION



FLIGHT LINE SW-1

Figures 36. Selected spectral curves from the Sweet Water Mountain test site. Very strong clay bands are present despite the heavy snow cover.

IV CONCLUSIONS AND RECOMMENDATIONS

The airborne spectroradiometer has shown to be an important potential tool for mineral exploration and geologic mapping. The results of these first reconnaissance survey lines show that the various mineral bands are clearly visible in the operational airborne mode. Previous data of this spectral resolution was available only from laboratory measurements on rock samples. The airborne data show that the same mineral features used in the laboratory to identify specific mineral species can be used in the field for rapid mapping of hydrothermal alteration and other mineralogies from the air.

The present data indicate that several areas of research will be very important in further developing ground and airborne infrared spectral sensing techniques. There are many new spectral features of either minerals or groups of minerals that have been observed in the present data. Both ground measurements and sampling in the present survey areas, and laboratory studies, are needed to expand our present knowledge of the infrared spectral properties of materials and natural targets. The present study observed a limited number of sites. The number of sites should be increased to other well known geologic areas with established ground data for verification. The airborne spectroradiometer system coupled with ground verification offers a very good and rapid technique for studying

the infrared properties of natural geologic areas.

The information contained in the high resolution spectral data cannot be obtained with lower resolution and limited band instruments. The natural point to begin in design of possible specialized lower resolution systems for wide area imaging, and in the formulation of applications concepts, is with high resolution spectroradiometer applications and research surveys. These surveys under the optimum spectral resolution and radiometric sensitivity will prove, first, the kinds of results that can be achieved, and second, specifically how to design the technology to achieve the optimum results.

The present research survey results have shown that there will be very important applications in mineral and hydrocarbon exploration using both spectroradiometers and narrow band infrared imagers for airborne mapping and geologic reconnaissance.

REFERENCES

1. Chiu, Hong-Yee, and W. Collins, 1978, A spectroradiometer developed for airborne remote sensing applications: Photogrammetric Engineering and Remote Sensing 44, 507.
2. Collins, William, 1978, Analysis of airborne spectroradiometric data and the use of LANDSAT data for mapping hydrothermal alteration: Geophysics, Vol. 43, No. 5, P. 967 - 987.
3. Collins, William, Chang, Sheng-Huei, Kuo, John T., 1981a, Detection of hidden mineral deposits by airborne spectral analysis of forest canopies: Final Report to National Science Foundation.
4. Collins, William, Chang, Sheng-Huei, Kuo, John T., 1981b, Biogeochemical laboratory studies to establish the spectral properties of mineral-induced stress in plants: Final Report to National Science Foundation.
5. Hunt, G.R., 1979, Near-infrared (1.3 - 2.4 m) spectra of alteration minerals - Potential for use in remote sensing: Geophysics, Vol. 2, P. 1974 - 1986.